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(54) Title: AN OPTICAL FIBRE ARRANGEMENT			
(57) Abstract			
<p>An optical fibre arrangement (70) comprising at least two optical fibre sections (71, 72), the optical fibre sections each having an outside longitudinally extending surface, and the outside longitudinally extending surfaces being in optical contact with each other. In a preferred embodiment, there is disclosed a parallel optical amplifier.</p>			

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## AN OPTICAL FIBRE ARRANGEMENT

### Field of the Invention

This invention relates to an optical fibre arrangement, optical fibre lasers and optical fibre amplifiers. The optical fibre amplifier may be a parallel optical amplifier, and the parallel optical fibre amplifier probably has the most far-reaching commercial applications in optical telecommunication networks.

### Background of the Invention

There is a demand for optical amplifiers that can output powers of 1 W or greater, can amplify many wavelength channels simultaneously with low cross-talk and low inter-channel interference, and can do so with high reliability and low cost per wavelength channel.

In many applications such as dense wavelength division multiplexing (WDM) transmission systems and satellite communications, optical amplifiers and transmitters, optically pumped by, e.g., laser diodes, should not only be capable of handling relatively high power but also be protected against failure of pump sources.

Conventional optical amplifiers use single-mode optical fibre whose core is doped with one or more rare-earth ions such as Erbium. Such amplifiers provide limited power output that is insufficient for multi-channel WDM transmission systems. In addition, conventional amplifiers are prone

to the failure of pump sources, requiring several pump sources to be contained with the amplifier in order to provide pump redundancy – but at high cost.

The power output of conventional optical amplifiers has recently been increased by the introduction of pump modules containing several semiconductor lasers whose outputs are wavelength division multiplexed into a single optical fibre. Although the output power obtainable from such an optical amplifier containing one of these pump modules is sufficient for amplifying many channels simultaneously, the approach is expensive and offers limited pump redundancy.

Higher-power optical amplifiers and fibre lasers can be constructed using double-clad optical fibres containing a single-mode waveguiding core doped with rare-earth ions (such as Erbium or Erbium/Ytterbium) and a multi-mode inner cladding formed by the silica cladding guiding against an outer cladding with lower refractive index. This outer cladding is typically a polymer outer cladding. However, it is cumbersome to separate the signal path to the single-mode core from the path required to launch pump powers into the inner cladding. Several techniques have been tried including separating the beams with dichroic mirrors, side pumping using a multimode coupler, and etching pits into the double-clad fibre. However, none of these techniques provides a simple, effective way of reliably introducing the pump energy into the optical amplifier or fibre laser – especially if several pump

lasers are required in order to provide pump redundancy. This issue is of concern for high-power fibre lasers where there is a requirement to introduce the pump energy from several to tens of pump diodes into the laser cavity. No effective, reliable and cost-effective way to achieve this exists in the prior art.

An associated problem is that introducing signal conditioning into the optical amplifier can be difficult. For example, it is often desirable to compensate for the spectral gain variation within the optical amplifier, or to introduce a filter to compensate for the dispersion in a telecommunication link. This requires ready access to the signal, which can be difficult for most amplifier configurations. A requirement therefore exists for an amplifier and laser design where it is simple to insert added functionality.

Today's optical telecommunications networks are increasingly based on wavelength division multiplexing – the simultaneous transmission of many wavelength channels through the same fibre. As the networks expand, these wavelength channels can originate from different locations. This places stringent demands on the management of the network, especially on the performance of optical amplifiers dispersed throughout the network. The wavelength channels arriving at an optical amplifier are unlikely to have equal powers (ie they are unbalanced), and the power of an individual wavelength channel can be suddenly and unexpectedly increased. This unbalance and the changing of the power levels in individual channels is

referred to as granularity. Prior art optical amplifiers experience problems with unbalanced wavelength channels in that the highest power wavelength channel may be amplified more than the other channels, thus increasing the unbalance. In addition, the sudden changing of the power level in one wavelength channel can cause instabilities in the optical amplifier. One of the most robust solutions to remove the granularity is to separate all the wavelength channels prior to amplification, amplify the channels, and then recombine the channels for retransmission. The major problem with this approach is that networks can transmit over one hundred wavelength channels through a single optical fibre. The cost of prior-art optical amplifiers makes this solution unattractive.

The cost issue of optical amplifiers is also a problem as the networks expand into the metropolitan areas, the expansion being driven by the insatiable demand for bandwidth for internet, data, mobile phones and cable television. Prior art optical amplifiers are too expensive and this is currently limiting the expansion of the networks.

Erbium-doped fibre amplifiers have revolutionized optical telecommunications over the last ten years. They are finding more and more uses, for instance for compensation of switching losses. The increasing need for capacity in telecommunication networks drives not only amplification requirements, e.g., output power and gain flatness for wavelength division multiplexing applications, but also the required number of amplifiers in a

system. Erbium doped fibre amplifiers have remained "stand-alone" devices, with individual amplifiers separately packaged. Component count as well as cost then holds back penetration of the optical amplifiers into different application areas that require a large number of amplifiers at a low cost. Instead, the drive has been towards purpose-built optical amplifiers with high specifications (bandwidth and output power) for use in applications that can tolerate a high cost.

It is therefore an aim of the present invention to obviate or reduce the above mentioned problems.

#### **Summary of the Invention**

According to a non-limiting embodiment of the present invention, there is provided an optical fibre arrangement comprising at least two optical fibre sections, the optical fibre sections each having an outside longitudinally extending surface, and the outside longitudinally extending surfaces being in optical contact with each other.

The invention further includes an optical amplifier constructed from such an optical fibre arrangement, and especially a parallel optical amplifier with multiple amplifying fibres. This invention is believed to have far-reaching commercial application in optical telecommunication networks.

The apparatus and method of the invention may enable pump power to be conveniently coupled into optical amplifiers and lasers.

The apparatus and method of the invention may enable optical amplifiers and lasers to be constructed that are more immune to pump failure than are prior art devices.

The apparatus and method of the invention may enable optical amplifiers and lasers to be conveniently constructed having additional functionality.

The apparatus and method of the invention may enable a route for lower cost optical amplification that will have important application in optical networks.

The apparatus and method of the invention may reduce the effects of granularity in optical networks.

The apparatus and method of the invention may enable individual wavelength channels in WDM networks to be amplified and balanced.

The apparatus and method of the invention may enable high-power optical amplifiers and high-power fibre lasers to be constructed.

The invention also provides an optical fibre arrangement comprising a plurality of optical fibres each having an outside surface, and wherein the outside surface of at least two adjacent optical fibres are in optical contact along at least a respective portion of its length.



The optical fibre arrangement may comprise a plurality of optical fibres that are surrounded by a coating material along the length of the optical fibre arrangement.

The invention also provides a method for manufacturing an optical fibre arrangement comprising the following stages: providing a plurality of optical fibre preforms, mounting the plurality of optical fibre preforms in a fibre drawing tower, drawing a plurality of optical fibre from the plurality of optical fibre preforms under a drawing tension and at a drawing speed, twisting the plurality of optical fibre during the drawing process, the drawing tension and the drawing speed being selected such that the outside surface of at least two adjacent optical fibres are in optical contact along at least a respective portion of its length.

The plurality of optical fibres may be coated by passing the fibres through a coating cup filled with a coating material.

The invention also provides a method for manufacturing an optical fibre arrangement comprising the following stages: providing a plurality of optical fibres, pulling the plurality of optical fibre under a drawing tension and at a drawing speed, and twisting the plurality of optical fibre during the drawing process, the drawing tension and the drawing speed being selected such that the outside surface of at least two adjacent optical fibres are in optical contact along at least a respective portion of its length.

The invention also provides an amplifying optical device having an optical pump and an optical fibre arrangement comprising a plurality of lengths of at least one optical fibre, each length of the optical fibre having a longitudinally extending outside surface, the arrangement being such that the outside surfaces of at least two adjacent lengths of the optical fibre are in optical contact with each other.

The amplifying optical device may be an amplifier comprising a plurality of amplifying fibres, each having an input and an output, at least one pump optical fibre having two ends and a pump that supplies pump energy connected to the pump optical fibre, the amplifier being configured such that the pump energy is shared by the plurality of amplifying fibres.

The amplifying optical device may be an amplifier comprising at least one input fibre, a first multiplexer connected to the input fibre, a coupler, and at least one output port connected to the coupler, the amplifier being configured such that at least one of the amplifying optical fibres is connected to the first multiplexer and at least one of the amplifying optical fibres is connected to the coupler.

The invention also provides an amplifying arrangement comprising a plurality of optical amplifiers each having a plurality of amplifying optical fibres and further comprising a second multiplexer connected to each first multiplexer.

The amplifying optical arrangement may comprise a plurality of optical amplifiers and an optical device, the amplifying optical arrangement being configured such that the optical device is connected to at least one optical amplifier.

The optical device may be selected from the group comprising an optical router, an optical switch, a polariser, an isolator, a circulator, a grating, an optical fibre Bragg grating, a long-period grating, an acousto-optic modulator, an acousto-optic tuneable filter, an optical filter, a Kerr cell, a Pockels cell, a dispersive element, a non-linear dispersive element, an optical switch, a phase modulator, a Lithium Niobate modulator, and an optical crystal.

The invention also provides an amplifying optical device comprising a fibre arrangement formed as a coil of a plurality of turns of amplifying optical fibre, the fibre comprising a core and a cladding, the arrangement being such that the claddings of adjacent fibres of at least a pair of the turns touch one another.

The coil may be coated and the coil may comprise at least one amplifying optical fibre and at least one pump optical fibre.

An amplifying optical device such as a laser or an optical amplifier constructed from an uncoated coil has the following advantages compared to the prior art:

1. It is based on an all-glass amplifying fibre: This overcomes the power limitations associated with polymer outer claddings.
2. Has a single pump-guiding cladding with an embedded core, but no coating or outer cladding. This overcomes the problems with accessing the pump waveguide for side-splicing that arises in other all-glass structures.
3. Uses a glass-air waveguide for guiding the pump. This results in a high  $NA > 1$ .
4. Has a substantially reduced glass-air surface area compared to previous fibre laser designs. This reduces the losses that arise at such an interface.
5. Can be formed by coiling a fibre and fixing it (e.g., by fusing) into a rigid body.
6. Eliminates the requirement (in a prior-art cladding-pumped fibre amplifier or fibre laser) that the fibre from which this new structure is made must be able to guide the pump i.e., large enough and with sufficient NA (and assuming that the amplifier or laser structure is made by coiling a fibre). Thus, a fibre with a much smaller outer diameter and hence a much lower passive-cladding to active-core volume ratio (= area ratio) can be used. This improves pump absorption and thereby efficiency. Instead, it is enough that the structure as a whole can guide the pump. For instance, a pump coupler can be side-spliced to the structure rather than to a single point on a single fibre or the pump

energy may be introduced with a plurality of pump optical fibres that may of such a size that they can be located in the interstitial spaces within the coil.

7. Eliminates need for special geometries for improved pump absorption. In a prior-art cladding-pumped fibre, special measures like off-centre cores, non-circular claddings, or bending of the fibre to special geometries is normally needed to improve the pump absorption because some pump modes are otherwise absorbed too slowly. The disclosed structure may, at least to some extent, eliminate the geometrical similarities and symmetries between the pump waveguide and signal waveguide (core). This improves the pump absorption even in the absence of any further measures as described above.
8. Can be securely supported at a few points in space. This reduces any excess pump propagation loss that may arise at such supporting points, because these perturb the waveguiding air-glass interface.
9. Provides means for preventing pump light from leaking out through pump delivery fibres.

The invention also provides an optical fibre laser comprising an amplifying optical device comprising a pump source and an optical fibre arrangement, and an optical feedback arrangement for promoting light generation within the laser.

The invention also provides a method for reducing the granularity in optical telecommunications network, which method comprises providing at least one amplifying optical arrangements having a plurality of amplifying optical fibres in at least one location within the network.

The invention also provides an optical telecommunications network comprising at least one of the amplifying optical arrangements having a plurality of amplifying optical fibres.

#### **Brief Description of the Drawings**

Embodiments of the invention will now be described solely by way of example and with reference to the accompanying drawings in which:

Figure 1 is a diagram of a prior art fibre amplifier;

Figure 2 is a diagram of a prior art double clad fibre structure;

Figure 3 is a diagram of a prior art fibre laser;

Figure 4 is a diagram of a prior art pump scheme;

Figure 5 is a diagram of a prior art multiple pump scheme;

Figure 6 is a diagram of a prior art pump coupling scheme;

Figure 7 is a diagram of an embodiment of the present invention;

Figure 8 is a diagram of an embodiment of the present invention in which the optical fibre sections are from the same optical fibre;

Figure 9 is a diagram of an embodiment of the present invention in which the optical fibre sections are from different optical fibres;

Figure 10 is a diagram of an embodiment of the present invention where the fibres have different diameters;

Figure 11 is a diagram of an embodiment of the present invention in which the optical fibre sections are fused together;

Figures 12 to 19 depict various optical fibre arrangements with a plurality of first and second optical fibres according to the present invention;

Figure 20 depicts an optical fibre arrangement according to the present invention including a holey fibre;

Figure 21 depicts an optical fibre arrangement according to the present invention in which the optical fibre sections are twisted with respect to each other;

Figure 22 depicts an optical fibre arrangement according to the present invention in which a pump optical fibre is twisted around an amplifying optical fibre;

Figure 23 depicts an optical fibre arrangement according to the present invention in which a pump optical fibre is twisted around two amplifying optical fibres;

Figure 24 depicts an optical fibre arrangement according to the present invention in which six second optical fibres are twisted about a first optical fibre;

Figure 25 depicts an optical fibre arrangement according to the present invention in which third optical fibres are twisted around first and second optical fibres;

Figure 26 depicts an optical fibre arrangement according to the present invention in which the optical fibre sections are coated;

Figure 27 depicts an apparatus for manufacturing an optical fibre arrangement according to the present invention;

Figure 28 depicts an apparatus for manufacturing an optical fibre arrangement having a coating according to the present invention;

Figure 29 depicts an optical fibre arrangement according to the present invention in which the optical fibre sections are held together with an optical glue;

Figure 30 depicts an amplifying optical device according to the present invention;

Figure 31 depicts an amplifying optical device according to the present invention in which a pump optical fibre is twisted around an amplifying optical fibre;



Figure 32 depicts an amplifying optical device according to the present invention comprising two pump optical fibres;

Figure 33 depicts an amplifying optical device according to the present invention comprising two amplifying optical fibres;

Figures 34 to 36 depict an amplifying optical device according to the present invention in which the amplifying optical fibres are joined together in different ways;

Figure 37 depicts an amplifying optical device according to the present invention and including an optical element;

Figure 38 depicts an amplifying optical device according to the present invention in which the optical element is an optical fibre Bragg grating;

Figure 39 depicts an amplifying optical device according to the present invention in which the optical element connects two amplifying optical fibres;

Figure 40 depicts an amplifying optical device according to the present invention in which an optical element and a reflecting device are configured to reflect optical energy to the same amplifying optical fibre;

Figure 41 depicts an amplifying optical device according to the present invention in which an amplifying optical fibre is configured in a coil;

Figure 42 depicts an amplifying optical device according to the present invention in which an amplifying optical fibre is configured in a coil and including a pump optical fibre;

Figure 43 depicts an amplifying optical device according to the present invention in which an amplifying optical fibre and multiple pump optical fibres are configured in a coil;

Figure 44 depicts an amplifying optical device according to the present invention in which multiple amplifying optical fibres are configured in a coil;

Figure 45 depicts an amplifying optical device according to the present invention in which at least one pump optical fibre is disposed in interstitial gaps between turns of at least one amplifying optical fibre;

Figure 46 depicts an amplifying optical device according to the present invention in which an amplifying optical fibre is wound around a former;

Figure 47 depicts an amplifying optical device according to the present invention in which an amplifying optical fibre and a pump optical fibre are wound around a former;

Figure 48 depicts a laser according to the present invention;

Figure 49 depicts a laser according to the present invention configured as a ring laser;

Figure 50 depicts an optical amplifier according to the present invention;

Figure 51 depicts an amplifier according to the present invention comprising a first multiplexer;

Figure 52 depicts an amplifying optical arrangement according to the present invention;

Figure 53 depicts an amplifying optical arrangement according to the present invention comprising an optical device;

Figure 54 depicts an optical network according to the present invention;

Figure 55 depicts a power splitter according to the present invention;

Figure 56 depicts a serial power splitter according to the present invention;

Figure 57 depicts a power splitter and amplifiers according to the present invention;

Figure 58 depicts an amplifier according to the present invention;  
and

Figures 59 to 62 depict performance results measured on an amplifier according to the present invention.

### Detailed Description of Preferred Embodiments of the Invention

Figure 1 shows a schematic diagram of a conventional optical amplifier 10 according to prior art. The optical amplifier 10 is based on an erbium (Er) – doped optical fibre 11 that is optically pumped by two pump lasers 12 whose pump energy is coupled into the Er-doped optical fibre 11 via first and second wavelength division multiplexers 14 and 15. An input signal 16 is coupled into the Er-doped optical fibre 11 via the first wavelength division multiplexer 14, is amplified by the Er-doped optical fibre 11, and is coupled to an output port 17 via the second wavelength division multiplexer 15.

The Er-doped optical fibre 11 is a single mode optical fibre containing the erbium doping within its core. Thus the single mode core guides both the signal 16 and the pump energy from the pump lasers 12.

As can be seen from Figure 1 a conventional amplifier does not offer any pump redundancy: If one of the pump lasers 12 fails, the gain of the amplifier 10 drops significantly. Moreover today's semiconductor-diode pump lasers can deliver no more than about 200 mW of power into a single-mode fibre. This limited pump power imposes limits on achievable signal power that can be output from the amplifier 10.

Recently Spectra Diode Labs Inc of San Jose, California, USA has developed a wavelength-multiplexed pump module. This source combines the output of up to four pump modules to obtain up to 500 mW of pump

power [see for example Spectra Diode Labs product catalogue, part # SDLO WM4]. In this module four individual pumps are spectrally separated by 5 nm so that all pumps are within the erbium absorption band. This method offers some protection against failure of pump diodes, but the module itself is quite expensive and cannot be easily upgraded to a greater number of pumps due to the relatively narrow absorption peak of erbium ions in silica glass in the wavelength region around 980 nm [see for example E. Snitzer, H. Po, R. Tumminelli, P. Hakimi, US Patent # 4,815,079].

An approach to increase the signal power available from an optical amplifier was suggested in V. P. Gapontsev and I. Samartsev, WO95/10868: the use of a so-called double-clad fibre for cladding-pumping. The principle is shown in Figure 2. A double-clad fibre 21 comprises a core 23, a primary (inner) cladding 24, and a secondary (outer) cladding 25. Pump light 22 is launched directly into the primary cladding 24, which is capable of guiding light due to the presence of the secondary cladding 25 which has a lower refractive index than the refractive index of the primary cladding 24. The secondary cladding 25 is typically a polymer coating that is applied during the manufacture of the double-clad fibre 21.

In this type of optical amplifier, the core 23 is usually doped with rare-earth ions, while the pump light 22 is launched into the primary cladding 24. Typically, the diameter of the core 23 is in the region of 5 – 25  $\mu\text{m}$  and the refractive index difference between the core 23 and the primary

cladding 24 is between  $3 \times 10^{-3}$  and  $1 \times 10^{-2}$ . A relatively large diameter of the primary cladding 23 allows the use of broad stripe, semiconductor-laser pump diodes with 1 to 5 W of pump power obtained from a  $100 \mu\text{m} \times 1 \mu\text{m}$  stripe. The result is that cladding pumped fibre amplifiers based on the double-clad fibre 21 can deliver much higher output power in comparison with the conventional, core-pumped amplifier 10.

Figure 3 shows the double-clad fibre 21 configured as a fibre laser 31. In this configuration, a pump beam 32 is launched through a dichroic mirror 33 into the double-clad fibre 21. A high-reflectivity mirror 34 is used to reflect back both pump and signal. The resulting signal 35 from the fibre laser 31 is separated from the pump beam 32 by the dichroic mirror 33.

Cladding-pumped optical amplifiers can be constructed using dichroic mirrors in similar configurations to the fibre laser 31 shown in Figure 3. However, a problem associated with this and many other experimental devices based on double-clad fibres 21 is that it is difficult to access the signal of the fibre laser or amplifier because it is necessary to use one or both ends of the double-clad fibre 21 for launching pump power. A further limitation is that at most two pump diodes can be launched into the double-clad fibre 21 unless complex polarisation or wavelength division multiplexed schemes are used. End-pump configurations of fibre lasers and amplifiers according to the prior art such as shown in Figure 3 offer limited pump redundancy.

Figure 4 shows a multimode fibre coupler 40. An auxiliary pump optical fibre 41 is used to launch pump light 42 into a double-clad fibre 21 that is doped with rare-earth ions in its core 23. The resulting amplified spontaneous emission provides an output signal 43 from both ends of the double-clad fibre 21.

A main advantage of this scheme is that both ends of the double-clad fibre 21 are now accessible for launching and out-coupling signal power for signal manipulation [see for example D. J. DiGiovanni, R. S. Windeler, A. M. Vengsarkar, J. L. Wagener, US Patent # 5802236]. Furthermore, this scheme can offer protection against pump diode failure using multiple auxiliary pump optical fibres 41 as shown in Figure 5. The solution shown in Figures 4 and 5 is therefore highly flexible allowing many configurations of fibre lasers and amplifiers to be constructed.

However, a major problem associated with the use of the multimode fibre coupler 40 is it is necessary to remove the secondary cladding 25 in order to attach the auxiliary pump optical fibre 41 to the double-clad fibre 21. This is a difficult process, resulting in a numerical aperture (NA) mismatch and potential reliability issues.

An important parameter for double-clad fibres is the numerical aperture for the inner cladding. This depends on the refractive indices of the inner and outer cladding. The refractive index of the inner cladding is determined by choice of material, a choice that depends on several other

parameters besides the refractive index. Fused silica is one preferred material for the inner cladding, with a refractive index of 1.45. This is rather low, which makes it difficult to find a material for the outer cladding with a desired, much lower, refractive index. A polymer cladding is one possibility. For instance, silicone rubber would lead to an NA for the inner cladding of 0.4.

While 0.4 is a relatively large numerical aperture, polymer coatings may suffer from rather low power handling capability and a relatively high loss. An all-glass structure with a glass outer cladding is preferred from these points of view. However, even a low-index glass like fluorosilicate leads to an NA of only 0.25 with a pure fused silica inner cladding. This low NA imposes certain limitations on the performance of cladding pumped fibre lasers and amplifiers. The main constraint arises from the brightness theorem. This is a fundamental governing law that dictates system design. It states that the brightness  $J$  of an optical system can not be increased by passive means, and this can be written as

$$J_{\text{pump}} = \frac{P_{\text{pump}}}{A_{\text{eff}}^p \cdot \Omega_x \Omega_y} \geq J_{\text{fibre}} = \frac{P_{\text{fibre}}}{A_{\text{eff}}^f \cdot \text{NA}^2}$$

where  $A_{\text{eff}}^j$  is an effective cross section of the pump diode or fibre,  $\Omega_i$  is the pump diode divergence in fast and slow directions and NA is the numerical aperture of the fibre for the pump beam.



Currently, laser diodes offer brightness in the region of  $0.3 \text{ W}/\mu\text{m}^2$  (assuming 2 W,  $100 \mu\text{m} \times 1 \mu\text{m}$  stripe and  $0.7 \times 0.1 \text{ NA}$ ). For reliability reasons the pump diodes are often down-rated by a factor of 4, so that the real brightness is in the region of  $0.1 \text{ W}/\mu\text{m}^2$ . Thus for example, a 10 W fibre laser system requires about 50 W of pump power delivered by 25 to 50 pump diodes (assuming 20% overall optical efficiency). If the system is based on a fibre with inner and outer claddings of different glass materials with an NA of 0.25 for typical choices of glasses, the fibre outer diameter (OD) should be greater than  $100 \mu\text{m}$ . Thus even a modest 10 W of output power would require a fibre OD greater than  $100 \mu\text{m}$ . For 200 W lasers the fibre OD should be in the region of 1 mm. This creates problems in that the large inner cladding reduces the interaction between the pump beam and the core. Therefore, even longer fibres are required.

A typical double-clad fibre with a silica inner cladding according to the prior art can either have a low-index polymer coating with a high NA and low power handling, or a relatively higher index glass outer cladding with a low NA but that can handle high powers well. Both of these options impose limits on the design and performance of high-power fibre lasers.

Recently, a new approach to an all-glass structure with a high NA has been demonstrated [D. J. DiGiovanni, R. S. Windeler, A. M. Vengsarkar, J. L. Wagener, US Patent # 5802236]. The basic idea is to let the pump waveguide be formed by glass surrounded by air, with  $\text{NA} > 1$ .

The structure is then supported by a thin outer glass shell that surrounds the fibre and runs along its length. However, this type of fibre is not readily used together with the pump-couplers of Figures 4 and 5. Moreover, because of the large difference in refractive indices between air and glass, it is quite difficult to make a pump waveguide with sufficiently low loss.

It is also difficult to use the pump couplers in Figures 4 and 5 with all-glass double-clad fibres: it is difficult to remove the glass outer cladding, as is required for efficient coupling. Even the polymer-clad fibre presents problems for the pump coupler: while it is easy to remove the outer cladding to expose the inner cladding for pump coupling, the coating at the point on the fibre where the coating reappears will absorb a large fraction of the power lost in the device, since at this point, any mode that is guided by the glass-air interface, but not by the glass-polymer interface, will be absorbed. This can cause the coating to burn, and therefore limits the power that the coupler can handle.

With reference to Figure 7, there is provided an optical fibre arrangement 70, which optical fibre arrangement 70 comprises at least two optical fibre sections 71, 72, the optical fibre sections 71, 72 each having an outside longitudinally extending surface 73, and the outside longitudinally extending surfaces 73 being in optical contact with each other.

By optical contact there is meant that light propagating in the near surface region in one of the adjacent optical fibre sections 71 can penetrate

into the near-surface region of the other adjacent optical fibre section 72. This will clearly not be the case if one of the optical fibre sections is coated with a typical coating such as an acrylate or silicone compound.

The optical fibre sections 71, 72 may be of constant cross-section along their length.

The optical fibre sections 71, 72 can comprise a core and at least one cladding. The core can be circular or non-circular. The core can be in the located in the centre of the cladding or offset from the centre. The cladding can be circular or non-circular. One or more of the optical fibre sections 71, 72 can comprise a glass rod that can be silica or soft glass.

The optical fibre sections 71, 72 can be constructed from the same optical fibre 81 as shown in Figure 8, or from different optical fibres 91, 92 as shown in Figure 9.

Figure 10 shows a cross-section through an optical fibre arrangement in which a first optical fibre 101 having a core 103 and a cladding 104 is in optical contact with a second optical fibre 102 having only a cladding 105. The first optical fibre may be a single-mode or multi-mode optical fibre and the second optical fibre 102 may be silica rod. The optical fibre arrangement is preferably constructed from freshly drawn optical fibre.

Figure 11 shows a similar optical fibre arrangement in which a first optical fibre 111 is fused to a second optical fibre 112. The optical fibres are preferably fused during the fibre drawing process (in which the optical

fibre is manufactured) or subsequently. The first and second optical fibres 111, 112 may be single-mode or multi-mode optical fibres.

Figures 12 to 20 show alternative optical fibre arrangements in which at least one first optical fibre 120 is optically connected to at least one second optical fibre 121. Each of the first and second optical fibres 120, 121 can have a circular cross section or a non circular cross section, and either or both the first and second optical fibres 120, 121 can each contain waveguiding cores that can be situated in the centre of the optical fibre 120, 121 or offset from the centre.

The first and second optical fibres 120, 121 can be formed from a glass selected from the group comprising silica, doped silica, silicate, phosphate, and soft glass.

The first optical fibre 120 can be an amplifying optical fibre doped with rare-earth ions.

The amplifying optical fibre preferably has a single multimode cladding and a waveguiding core. The core and/or cladding can comprise at least one rare earth dopant selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium, Dysprosium or is doped with a transition metal or semiconductor. The core and/or cladding can be co-doped with Erbium/Ytterbium. The core and/or cladding can be doped with germanium, phosphorous, boron, aluminium and/or fluoride. The core diameter can be substantially in the range of 2  $\mu\text{m}$

to 100  $\mu\text{m}$ . The cladding area can be at least 10 to 1000 times larger than the cross sectional area of the core.

More than one amplifying optical fibre may be included in the optical fibre arrangement 70, each one of the amplifying optical fibres containing the same dopants or different dopants.

The second optical fibre 121 can be a pump optical fibre, the pump optical fibre being in optical contact with the amplifying optical fibre along at least a portion of its length.

Figure 20 shows a cross-section through an amplifying optical arrangement 70 in which the first optical fibre 120 is a so-called "holey fibre" 201 (or "photonic bandgap fibre") that comprises a waveguide constructed from a lattice of azimuthal holes 202 extending along the axis of the fibre 201. The holey fibre 201 may be doped with one or more of the rare earth dopants selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium, Dysprosium or is doped with a transition metal or semiconductor. The core and/or cladding can be co-doped with Erbium/Ytterbium. The lattice may be a regular lattice or an irregular lattice.

The second optical fibre 121 can be a pump optical fibre, the pump optical fibre being in optical contact with the holey fibre 201 along at least a portion of its length. The amplifying optical arrangement may contain a single second optical fibre 121 or a plurality of second optical fibres 121.

The second optical fibre 121 can be a pump optical fibre, the pump optical fibre being in optical contact with the amplifying optical fibre along at least a portion of its length.

Figure 21 shows an optical fibre arrangement in which the optical fibre sections 71, 72 are twisted about each other. The term "twisted" is being used here in a very general sense as is illustrated in Figures 22 and 23 where a pump optical fibre 221 is shown twisted around at least one amplifying optical fibre 222. The pump optical fibre 221 is shown as having a diameter very much less than that of the amplifying optical fibre 222. The amplifying optical fibres 222 in Figure 23 are shown in optical contact with each other and with the pump optical fibre 221.

The amplifying optical fibre 222 preferably has a single multimode cladding and a waveguiding core. The core and/or cladding can comprise at least one rare earth dopant selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium, Dysprosium or is doped with a transition metal or semiconductor. The core and/or cladding can be co-doped with Erbium/Ytterbium. The core and/or cladding can be doped with germanium, phosphorous, boron, aluminium and/or fluoride. The core diameter can be substantially in the range of 2  $\mu\text{m}$  to 100  $\mu\text{m}$ . The cladding area can be at least 10 to 1000 times larger than the cross sectional area of the core. The rare earth dopant can be disposed

in the core, in the cladding, in regions in the core and the cladding, or in a ring around the core.

More than one amplifying optical fibre 222 may be included in the optical fibre arrangement 70, each one of the amplifying optical fibres 222 containing the same dopants or different dopants.

The amplifying optical fibre 222 may comprise a waveguide constructed from so-called "holey fibre" or "photonic bandgap fibre" and may be doped with one or more of the rare earth dopants. The pump optical fibre 221 can have a substantially uniform refractive index across its cross-section and may be drawn from a silica rod.

Figure 24 shows a first optical fibre 241 and six second optical fibres 242 twisted together in a such way that the outside surface of at least two adjacent fibres are in optical contact along at least a respective portion of the length of the optical fibre arrangement. The first optical fibre 241 can be the amplifying optical fibre 222, and the second optical fibre 242 can be the pump optical fibre 221. Alternatively the first optical fibre 241 can be the pump optical fibre 221 and the second optical fibre 242 can be the amplifying optical fibre 222.

Figure 25 demonstrates yet another arrangement in which four first optical fibres 241 and three second optical fibres 242 are straight, and two third optical fibres 243 are twisted around the first and second optical fibres 241 and 242.

Figure 26 shows an optical fibre arrangement in which the optical fibre sections 71, 72 are surrounded by a coating material 262 along a length of the optical fibre arrangement. For clarity, the optical fibre sections 71, 72 are shown extending and separating on either side of the coating material 262.

The coating material can be a polymer with a refractive index less than the refractive index of a cladding material of at least one of the optical fibre sections 71, 72. The coating material can be silicone rubber. The optical fibre sections 71, 72 may be a section of the amplifying optical fibre 222 and/or a section of the pump optical fibre 221.

Advantageously, one of the optical fibre sections 71, 72 can be individually separated by pulling from the remaining optical fibre section or sections 71, 72. This is a very desirable feature that has far-reaching commercial significance for the design and manufacture of a range of optical fibre amplifiers and lasers. It radically simplifies the problem of coupling of multiple pump sources to an optical fibre amplifier or fibre laser. It also enables parallel (ie multi-channel), optical amplifiers to be constructed, which are believed to have major cost and reliability advantages over the prior art.

Figure 27 shows an apparatus for manufacturing long lengths of an optical fibre arrangement in the form of an optical fibre cable 277. A first and second optical fibre preform 271, 272 is placed in a chuck 273 on a fibre



drawing tower 270 and lowered into a furnace 274. A first and second optical fibre 275, 276 is drawn from the first and second optical fibre preforms 271, 272, twisted together, and wrapped around a drawing drum 278, which rotates at a given speed. The first and second optical fibres 275, 276 are drawn by rotating the drawing drum 278, and rotating the first and second optical fibre preforms 271, 272 while lowering the first and second optical fibre preforms 271, 272 into the furnace. The first and second optical fibres 275, 276 may be twisted together by rotating the chuck 273.

Figure 28 shows a similar apparatus, which includes a coating cup 281 containing a coating material 282 that is cured in a curing apparatus 283 during the fibre drawing process. The curing apparatus can be a furnace or a UV curing chamber depending on the type of coating material being applied.

The invention therefore provides the following method for manufacturing an optical fibre arrangement comprising: providing a first and second optical fibre preform 271, 272; mounting the first and second optical fibre preforms 271, 272 in a chuck 273 on a fibre drawing tower 270; drawing a first and second optical fibre 275, 276 from the first and second optical fibre preforms 271, 272 under a drawing tension and at a drawing speed; and twisting the first and second optical fibre 275, 276 during the drawing process; the drawing tension and the drawing speed being selected such that the outside surface of the first and second optical fibres 275, 276 are in optical contact along at least a respective portion of its length. The

first and second optical fibres 275, 276 can be passed through a coating cup 281 during the manufacturing process.

It will be appreciated that it will not always be convenient or practicable to manufacture an optical fibre arrangement directly during the fibre drawing process. The above method can be modified by using uncoated optical fibre, which may be unwound from drums. Such a method would comprising the following stages: providing a first and second optical fibre 275, 276; pulling the first and second optical fibres 275, 276 under a drawing tension and at a drawing speed; and twisting the first and second optical fibres 275, 276 during the drawing process; the drawing tension and the drawing speed being selected such that the outside surface of the first and second optical fibres 275, 276 are in optical contact along at least a respective portion of its length. The first and second optical fibres 275, 276 can be passed through a coating cup 281 during the manufacturing process. It may be convenient to apply a coating to the first and second optical fibres 275, 276 when they are first manufactured that can be removed immediately prior to manufacturing the optical fibre arrangement. Care needs to be taken to ensure that the surface of the optical fibre is not damaged during such removal of the coating.

Referring again to Figure 26, the coating material 262 may also be a glass having a refractive index less than the refractive index of the pump optical fibre 221. The glass may be applied using a sol-gel process. The

glass may be silica glass, a doped silica glass, or a soft glass.

Advantageously, the glass can be leached away for example by acid etching to expose the pump optical fibre 221 and the amplifying optical fibre 222 for subsequent connection to optical devices.

Figure 29 shows a cross-section of an optical fibre arrangement in which the first and second optical fibre sections 71, 72 are joined together by an optical glue 291. An optical glue in this context means that in an arrangement where two adjacent fibres are in close proximity but separated by a thin layer made of optical glue, then light can propagate from one of the fibres to the other through the optical glue layer.

Figure 30 shows an amplifying optical device 300 comprising the optical fibre arrangement 70 and a pump source 302.

The optical fibre arrangement 70 may be an amplifying optical fibre 222, a pump optical fibre 221. The pump optical fibre 221 and the amplifying optical fibre 222 are shown in optical contact with each other and thus pump energy propagating along the pump optical fibre 221 couples through to the amplifying optical fibre 222.

The pump optical fibre 221 preferably has a small diameter than the diameter of the amplifying optical fibre 222.

An optical amplifier based upon the amplifying optical device 300 preferably includes at least one optical isolator orientated to amplify an

optical signal at the input of the amplifier and a filter to filter out amplified spontaneous emission at the output of the amplifier.

The pump optical fibre 221 may have a reflecting device 225 deposited or positioned at or near its face. The reflecting device 225 may be an optical grating, a mirror, or a loop of optical fibre.

By amplifying optical device we mean an optical amplifier, a power amplifier, a laser, a broadband source of amplified spontaneous emission.

The amplifying optical fibre 222 can be a single-clad uncoated optical fibre.

The pump optical fibre 221 can be twisted around the amplifying optical fibre 222 as shown in Figure 31.

Figure 32 shows an amplifying optical device comprising an optical fibre arrangement 70 in which the optical fibre sections 71, 72 comprise one amplifying optical fibre 222 and two pump optical fibres 221, the amplifying optical fibre 222 and the pump optical fibre 221 being surrounded by the coating material 262. Each end of the pump optical fibres 221 is shown connected to a separate one of the pump sources 302. The figure illustrates the advantage of being able to individually separate the pump optical fibres 221 from the amplifying optical fibre 222. This configuration is especially useful for designing a high-power optical amplifier and moreover offers pump redundancy.

Figure 33 shows an amplifying optical device comprising two amplifying optical fibres 222. One of the important aspects to this embodiment is that the pump energy being supplied by the pump optical sources 302 is shared by more than one of the amplifying optical fibres 222 by virtue of the optical contact between the pump optical fibres 221 and the amplifying optical fibres 222. Further amplifying optical fibres 222 can be added and the amplifying optical device used as a parallel (or multi-channel) optical amplifier. Surprisingly, such an amplifier tends to equalise the output power provided by each of the amplifying optical fibres 222 by virtue of the shared pump energy between the amplifying optical fibres 222. Advantageously, each amplifying optical fibre 222 is capable of amplifying individual signals having different wavelengths with low cross-talk and low interference between signals having the same wavelength being amplified by different ones of the amplifying optical fibres 222.

Figures 34 to 36 show an amplifying optical device comprising a plurality of pump optical fibres 221 and a plurality of amplifying optical fibres 222, in which at least one end of the pump optical fibres 221 are connected to a pump source 302 supplying pump energy, and in which the optical fibre arrangement 70 is configured such that a portion of the optical energy guided by each of the pump optical fibres 221 is coupled into at least one of the amplifying optical fibres 222, and in which at least two amplifying optical fibres 222 are connected together. The amplifying optical devices shown in Figures 34 to 36 can comprise the coating 262.

The differences between the embodiments shown in Figures 34 to 36 is in the number of connections between the amplifying optical fibres 221 and in the connection of the pump optical fibres 221 to the pump sources 302. In Figure 34, the pump optical fibres 221 are joined together at one end of the amplifying optical device, whereas in Figures 34 and 36, each of the ends of the pump optical fibres 221 are connected to different pump sources 302. The advantage of joining the pump optical fibres 221 together is to achieve greater absorption of pump power. This should be compared with the advantages of pumping each of the optical fibres 221 from both ends, which are greater pump redundancy, increased saturation power and increased optical gain. The flexibility in the options for pumping the optical fibre arrangement 70 is an important advantage that is achieved with the present invention. The amplifying optical device shown in Figure 35 can be configured with a single pump source 302 although this will clearly reduce the pump redundancy and the saturated power.

The amplifying optical device shown in Figure 34 is a parallel (or multi-channel) optical amplifier that in effect comprises several amplifiers that share pump energy derived from common pump sources 302, wherein amplification in each amplifier is achieved in more than one pass through the optical fibre arrangement 70.

Figures 35 and 36 show amplifying optical devices wherein all the amplifying optical fibres 222 are joined together in series, the configurations

being high power optical amplifiers. The amplifying optical fibres 222 in Figure 35 are connected such that an optical signal would pass in both directions through the optical fibre arrangement 70 while being amplified, whereas the amplifying optical fibres 222 in Figure 36 are connected such that an optical signal would pass in the same direction through the optical fibre arrangement 70 while being amplified. In some cases it is preferable to configure the amplifying optical device as shown in Figure 36 - for example it may provide a lower noise figure. In other cases it is preferable to configure the amplifying optical device as shown in Figure 35 - for example it may provide higher gain.

The embodiments are similar to the parallel optical amplifier shown in Figure 34. The parallel optical amplifier of Figure 34 can be configured as the high-power optical amplifier of Figure 36 simply by connecting the amplifying optical fibres 222 together. It will therefore be appreciated that the parallel optical amplifier of Figure 33 provides significant flexibility in its use. These configurations also further illustrate that the importance of being able to individually separate the pump optical fibres 221 and the amplifying optical fibres 222 clearly increases as the numbers of pump optical fibres 221 and amplifying optical fibres 222 increases.

Figures 33 to 36 indicate the use of multiple pump optical sources 302. Clearly these embodiments will operate with a single pump optical

source 302. However, the use of multiple pump optical sources 302 provides pump redundancy and is therefore important.

Figure 37 shows an amplifying optical device 370 which includes an optical element 371 inserted along the length of the amplifying optical fibre 222, the optical element 371 being selected from the group comprising a polariser, an isolator, a circulator, a grating, an optical fibre Bragg grating, a long-period grating, an acousto-optic modulator, an acousto-optic tuneable filter, an optical filter, a Kerr cell, a Pockels cell, a dispersive element, a non-linear dispersive element, an optical switch, a phase modulator, a Lithium Niobate modulator, and an optical crystal.

The amplifying optical device 370 can be considered to be either a single amplifying optical device containing the optical element 371, or two amplifying optical devices connected together via the optical element 371.

The amplifying optical device 370 may comprise the coating 262. The amplifying optical device 370 may be constructed from an optical fibre arrangement 70 in which the amplifying optical fibre 222 can be individually separated by pulling from the remaining pump optical fibres 221, thus facilitating the insertion of the optical device 370. This is a very desirable feature that has far-reaching commercial significance for the design and manufacture of a range of optical fibre amplifiers and lasers. It radically simplifies the problem of adding more flexibility into the design of optical amplifiers and lasers.



Figure 38 shows an embodiment of the amplifying optical device of Figure 37 in which the optical element 371 is an optical fibre Bragg grating 382, and optical energy propagating in the amplifying optical fibre 222 is coupled into the optical fibre Bragg grating 382 via an optical circulator 381. The optical fibre Bragg grating 382 can be one or both of a gain-flattened grating and a dispersion compensating grating.. These are believed to be especially important embodiments of the present invention with application in telecommunication systems. By gain flattening, we mean that the fibre grating compensates for the spectral variation in the optical gain provided by the amplifying optical fibre 222. Figure 39 shows an amplifying optical device in which the optical element 371 connects two amplifying optical fibres 282.

Figure 40 shows an amplifying optical device in which the optical element 371 and a reflecting device 401 is configured to reflect optical energy being emitted from the amplifying optical fibre 222 back into the same amplifying optical fibre 222. The reflecting device 401 may be a mirror or an optical fibre Bragg grating. It will be appreciated that the amplifying optical device shown in Figure 40 can be configured as a laser by adding the second reflecting device 401 as shown. The laser can be configured as a Q-switched or a mode-locked laser.

Figure 41 shows an amplifying optical device comprising a single amplifying optical fibre 222 configured as a coil 411 such that at least two

adjacent turns of the single amplifying optical fibre 222 are in optical contact with each other. Optical pump power 412 can be coupled into the amplifying optical device by side illumination from at least one optical pump source 302 as shown in Figure 41, or by utilizing one of the prior art methods described in Figures 1 to 5.

The amplifying optical fibre 222 is preferably an unclad optical fibre that can be either single-mode or multimode, and have a circular or non-circular cross-section.

The coil 411 can be supported by at least one support 415. The support 415 can be a ceramic, glass or silica rod, tube, cylinder, or bead, epoxied or otherwise bonded to the coil 411. The support 415 may be a support means. The coil 411 can be enclosed within an enclosure, which may be sealed and evacuated, or filled with inert gas such as nitrogen or argon.

Figure 42 shows an amplifying optical device comprising a single amplifying optical fibre 222 configured as a coil 421 such that at least two adjacent turns of the single amplifying optical fibre 222 are in optical contact with each other, and including at least one pump optical fibre 221 disposed with respect to the coil 421 of amplifying optical fibre 222 so that the pump optical fibre 221 touches the amplifying optical fibre 222 along at least a respective portion of its length. As shown in Figure 43, the amplifying optical device can comprise a plurality of pump optical fibres

221 to form a coil 431. The amplifying optical fibre 222 and the pump optical fibres 221 are shown laying in a clockwise direction.

The amplifying optical device can comprise a plurality of amplifying optical fibres 222 as shown in Figure 44.. This is conveniently constructed by twisting the amplifying optical fibres 222 and at least one pump optical fibre 221 together to form an interim cable 442, and coiling the interim cable 442 to form a coil 441. The amplifying optical device of Figure 44 is a parallel optical amplifier with the performance advantages of the amplifying optical device described with reference to Figure 33.

The coils 411, 421, 431 and 441 can be potted in a polymer 443 as shown in Figure 44. The polymer 433 preferably has a refractive index lower than the refractive indices of the claddings of the amplifying optical fibres 222 and the pump optical fibre 221. The polymer 443 can be a silicone rubber.

The pump optical fibre 221 in Figures 42 to 44 can have a diameter much less than the diameter of the amplifying optical fibre 222. Advantageously, the pump optical fibre 221 can be disposed in interstitial gaps between turns of the amplifying optical fibre 222 as illustrated in Figure 45. The pump optical fibre 221 shown in Figure 45 can either be a single pump optical fibre or be many pump optical fibres – a configuration that is important for high-power amplifiers and lasers as well as providing a means to achieve pump redundancy.

The pump optical fibre 221 can be formed from a material having a lower melting point than the material of the amplifying optical fibre 222.

The coils 421, 431 and 441 in which one or more pump optical fibres 222 are attached can be considered to be a pumped coil. The number of pump optical fibres 221 can be between 1 and 100, or even higher for applications involving amplifiers and lasers requiring high power outputs (> 1 W to 5 W). The pump optical fibre 221 is preferably a multimode fibre fabricated either from silica or soft glass. For certain applications, it is convenient to have the pump optical fibre 221 smaller than the amplifying optical fibre 222, ie in the range 5  $\mu\text{m}$  to 100  $\mu\text{m}$ . For other applications, the pump optical fibre 221 should be of a comparable size or even much larger than the amplifying optical fibre 222. For example, when coupling to a diode bar, the pump optical fibre 221 can conveniently be in the region 100  $\mu\text{m}$  to 1000  $\mu\text{m}$  – the larger dimension clearly representing a glass rod that can be moulded into the pumped coil. The coil turns in the pumped coil can be melted to each other. The diameter of the pumped coil can be in the range 10 – 1000 times greater than the diameter of the amplifying optical fibre 222. Figure 46 shows a coil 461 comprising amplifying optical fibre 222 wound on a light transmitting former 462. Also shown is a pump arrangement 463 for launching pump light 464 into the former 462. The pump arrangement 463 can be the pump source 302. The amplifying optical fibre 222 has a longitudinally extending outside surface that is in optical

contact with the former 462 along at least a portion of the longitudinally extending outside surface.

Figure 47 shows a pump optical fibre 221 in optical contact with the former 462, the pump optical fibre 221 being connected to a pump source 302. In use, pump light will be coupled from the pump optical fibre 221 into the amplifying optical fibre 222 via the former 472.

An amplifying optical device in which the former 462 is a glass tube, a glass rod, a glass cylinder, or a glass hoop. In configurations involving a hoop, the coils can be conveniently wound around the hoop in a toroidal winding. The glass can be a soft glass, or can be silica or doped silica glass. Preferably, the refractive index of the glass should be substantially the same as the refractive index of the cladding of the amplifying optical fibre 222 and the pump optical fibre 221.

Figure 48 shows a laser 480 constructed from an amplifying optical device 481 by providing an optical feedback arrangement 482 for promoting light generation within the laser. The amplifying optical device 481 can be one of the amplifying optical devices described with reference to Figures 30 to 47. The optical feedback arrangement 482 can comprise two reflecting devices selected from the group comprising a mirror, a dichroic mirror, a coupler, an optical fibre coupler, and an optical fibre Bragg grating. The optical feedback arrangement 482 can be configured such that the laser 480 is a ring laser 490 as shown in Figure 49. Here, the optical feedback

arrangement 482 is shown as a coupler 491 to provide two output ports 492. If unidirectional operation is required, an optical isolator can be added into the ring according to prior art.

Figure 50 shows a preferred embodiment for an optical amplifier 500 configured as a parallel optical amplifier, which will be referred to frequently in the following description to demonstrate the major advantages of such a parallel amplifier in optical networks. The amplifier 500 contains the main advantages of the amplifying optical devices shown in Figures 30 to 47. The amplifier 500 comprises at least one pump source 302 for supplying pump energy, and a plurality of amplifying optical fibres 222. The amplifier 500 preferably comprises a plurality of pump optical fibres 221 – although as seen in Figure 41, this feature is not strictly necessary, and is not meant to limit either this embodiment or the embodiments that will be described in the following figures where the amplifier 500 is referenced. An important feature is that the pump energy provided by the pump source 302 (or any other pump arrangement) is shared between the plurality of the amplifying optical fibres 222 by virtue of the optical contact of the optical fibre sections 71,72 (not shown in Figure 50). The amplifier 500 can either be used for single-pass amplification, or for multi-pass amplification by connecting one amplifying optical fibre 222 to another amplifying optical fibre 222 as described in the description relating to Figures 34 to 36. The amplifier 500 provides a number of substantially independent amplification

channels that can simultaneously amplify signals at the same wavelength or at different wavelengths.

The pump source 302 preferably contains at least one semiconductor laser diode and there are preferably more than one pump source 302 connected to each of the ends of the pump optical fibre 221. The semiconductor laser diode can be a broad stripe laser diode or a diode bar. There is preferably more than one pump optical fibre 221 connected to additional pump sources 302. These features are preferred to increase pump redundancy, to increase the saturated power available from each amplifying optical fibre 222, and to amortize the investment of the relatively expensive semiconductor laser diodes over several amplifying optical fibres 222. This latter feature is especially important for applications requiring low-cost amplification, for example for application in metropolitan areas.

Figure 6 schematically illustrates a prior art technique for launching pump light from a laser diode 61 into the pump optical fibre 221. The pump light is emitted from an emission stripe 62 of the laser diode 61. As it has a much larger divergence in one dimension (vertically along the page as drawn), a cylindrical lens 63 formed as a piece of optical fibre is used to converge the pump light in this direction. The pump light is then launched into a fibre 64 in which at its end has a diameter of about 140-300  $\mu\text{m}$ , but which is then tapered down in a taper 65 to about 80  $\mu\text{m}$  for use in coupling to the pump optical fibre 221. The fibre 64 and the taper 65 may be

constructed from the same optical fibre, or different optical fibres, and may be a part of the pump optical fibre 221. This technique can also be used to launch light into other types of optical fibre.

Figure 51 shows an amplifier 510 comprising the amplifier 500, at least one input fibre 511 and a first multiplexer 512 connected to the input fibre 511. The amplifying optical fibres 222 are connected to the first multiplexer 512.

The first multiplexer 512 may be a coupler dividing the power essentially equally between its outputs. The coupler may be constructed from optical fibre couplers or may be a planar-optical device having a single input and multiple outputs.

The first multiplexer 512 can be a wavelength division multiplexer as an arrayed waveguide grating AWG. The first multiplexer 512 can also be an add multiplexer, a drop multiplexer, or an add-drop multiplexer constructed from thin-film filters and/or optical fibre gratings. The first multiplexer 512 can be used to separate out wavelength channels input by the input fibre 511 such that each amplifying optical fibre 222 amplifies either different wavelength channels or groups of different wavelength channels. The separate wavelength channels can be combined into a single output port 513 using a coupler 514 as shown in Figure 52. The coupler 514 can be a planar-optics coupler, one or more optical fibre couplers, a wavelength division multiplexer, an add multiplexer, a drop multiplexer, or



an add-drop multiplexer constructed from thin-film filters and/or optical fibre gratings. Figure 61 shows eight wavelength channels 611 to 618 output by an amplifier. Wavelength channels 611 and 612 are adjacent and so are wavelength channels 613 and 614. It is preferable that each amplifying optical fibre 222 amplifies only a single one of the wavelength channels.

Figure 52 shows an amplifying optical arrangement comprising a plurality of amplifiers 500 and a plurality of first multiplexers 512, and including a second multiplexer 521 connected to each first multiplexer 512 and to an input port 522. The second multiplexer 521 can be an interleaver that directs adjacent wavelength channels to different ones of the first multiplexers 512 and hence to different ones of the amplifiers 500 or a coupler that divides the input power between the two input fibres 511. The configuration with the interleaver is preferred. Thus referring to Figure 61, it is preferred that one of the amplifiers amplifies channels 611, 613, 615 and 617 whilst the other amplifier amplifies channels 612, 614, 616 and 618.

Figure 53 shows an amplifying arrangement comprising a plurality of amplifiers 500 and an optical device 531, the amplifying arrangement being configured such that the optical device 531 is connected to the amplifiers 500. The figure shows one of the pump optical fibres 221 being shared by two of the amplifiers 500 – thus saving on pump sources 302.

The optical device 531 can be an optical router, an add-drop multiplexer, an add multiplexer, a drop multiplexer, an optical switch, a polariser, an isolator, a circulator, a grating, an optical fibre Bragg grating, a long-period grating, an acousto-optic modulator, an acousto-optic tuneable filter, an optical filter, a Kerr cell, a Pockels cell, a dispersive element, a non-linear dispersive element, an optical switch, a phase modulator, a Lithium Niobate modulator, and an optical crystal. The optical device 531 can also be more than one of the above devices, either singly or in combination.

A preferred embodiment is where the optical device 531 is an optical router which comprises an optical switch configured such that optical signals output from one of the amplifiers 500 are routed to at least two more of the amplifiers 500.

The amplifying arrangements shown in Figures 51 to 53 have far reaching commercial application because they can be used to reduce the granularity from an optical telecommunications network. This granularity occurs when a signal at a remote location is suddenly turned on. This signal propagates through the optical network and can induce instabilities in an amplifier. The ability to separate out the individual wavelength channels into individual wavelength channels or groups of wavelength channels, each being amplified separately in the amplifier 500 reduces the cross-talk

inherent and instabilities which occur with prior art amplifiers, and does so in a cost effective manner.

Figure 54 shows an optical network 540 comprising at least one first optical fibre 541 that may be configured in at least one ring 545. The network includes at least one multi-wavelength transmitter 542 comprising a plurality of signal sources (not shown) that may be distributed feedback lasers, either directly modulated or with external modulation. The multi-wavelength transmitter 542 outputs a plurality of telecommunication signals 5402 into the first optical fibre 541 via a multiplexer 543 and/or a first add/drop multiplexer 544, each telecommunication signal 5402 having a different wavelength. An amplifier 5403 is shown in the ring 545.

A second add/drop multiplexer 546 may be included to remove at least one telecommunication signal 5402 from the first optical fibre 541 and transmit the telecommunication signal 5402 via a second optical fibre 547 to at least one location 5400. An amplifier 548, a coupler 549 and a third optical fibre 5401 may be included.

The telecommunication network 540 is not meant to be limited to the arrangement shown in Figure 54. There are many different topologies and architectures being explored today, including ring architectures and mesh architectures. However, the telecommunication network will always include the multi-wavelength transmitter 542 and the first optical fibre 541.

The amplifier 5403 may be the amplifying optical device shown in Figure 38 that includes an optical fibre Bragg grating to condition at least one telecommunication signal 5402.

The amplifier 5403 may be the amplifier 500.

The first add/drop multiplexer 544 may include an amplifier according to Figure 51 or an amplifying arrangement according to Figure 52 or Figure 53.

The second add/drop multiplexer 546 may include an amplifier according to Figure 51 or an amplifying arrangement according to Figure 52 or Figure 53.

The amplifier 548 may be an amplifying optical device according to any one of Figures 30 to 39, 41 to 44, 46, 47, an amplifier according to Figure 50 or Figure 51 or may include an amplifying arrangement according to Figure 52 or Figure 53. It will be noted that the amplifier 548 may be required to boost the telecommunication signal 5402 significantly in order that a signal with adequate signal to noise ratio is received at the location 5400.

The invention therefore provides a method to reduce the granularity in an optical telecommunications network comprising providing at least one of the amplifiers shown in Figures 50 and Figure 51, and/or at least one of the amplifying optical arrangements shown in Figures 52 or Figure 53 in at least one location within the network.

Figure 55 shows a power splitter 550 comprising at least one pump source 302 and an optical fibre arrangement 70 comprising a plurality of pump optical fibres 221 each having an input 555 and an output 556. The plurality of pump optical fibres 221 is configured in a coil 551, wherein at least one of the pump optical fibres 221 is connected to the pump source 302.

Provided that each of the pump optical fibres 221 has the same diameter, the optical power provided by the pump optical source 302 is divided approximately equally between the pump optical fibres 221 within the coil 551. The optical power provided by each output 556 of the pump optical fibres 221 can be predetermined by selecting the relative diameters of the pump optical fibres 221.

The pump optical fibres 221 may be twisted or may be left untwisted. The coil 551 can be constructed by forming an interim cable 552.

The coil 551 can be potted in a polymer 443. The polymer 443 preferably has a refractive index lower than the refractive indices of the claddings of the pump optical fibres 221. The polymer 443 can be a silicone rubber.

Figure 56 shows a power splitter 560 comprising at least one pump source 302 and at least one optical fibre arrangement 70 comprising a plurality of pump optical fibres 221 each having an input 565 and an output

566, wherein at least one of the pump optical fibres 221 is connected to the pump source 302. By varying the length of the optical fibre arrangement 70, the power splitting ratio at the output of the optical power splitter 550 can be set to a predetermined value.

The pump optical fibres 221 may be twisted or may be left untwisted.

Advantageously, the optical fibre arrangement 70 can be constructed from an optical fibre arrangement in which a first optical fibre is individually separable from a second optical fibre. For example, optical fibre arrangements based on the optical fibre 277 or the optical fibre 284. Such an approach provides a very cost-effective solution for sharing pump energy from a single pump source amongst a plurality of amplifiers, especially since many optical power splitters may be fabricated from a typical production quantity of the optical fibre 277 and the optical fibre 284.

Figure 57 shows optical pump power from a pump source 302 being divided by a power splitter 571 connected to a plurality of optical amplifiers 573 by output fibres 572. The output fibres 572 can be pump optical fibres 221. The power splitter 571 can be the power splitter 550 or the power splitter 560. The arrangement shown in Figure 57 provides a very cost-effective and reliable way of sharing output from a single pump source amongst several optical amplifiers.

Some detailed examples will now be presented of how pump light can be injected into amplifying optical fibres and converted into signal light. The results will be compared to a prior-art, double clad fibre laser.

### EXAMPLE I

This Example is based on the configuration depicted in Figure 32. The amplifying optical fibre 222 has an outer diameter (OD) of 200  $\mu\text{m}$  and a core diameter of 10  $\mu\text{m}$ . The core is single-moded at the signal wavelength and made of  $\text{Er}^{3+}/\text{Yb}^{3+}$ -activated aluminosilicate glass. The pump absorption cross section at 980 nm is 20-10-25  $\text{cm}^2$ . The  $\text{Yb}^{3+}$  concentration is 9000 particles per million (ppm). A 10 m long fibre absorbs  $\sim 90\%$  of launched pump power. The pump power is provided by 4 laser diodes with rated output power of 2 W. Using the simple launching scheme shown in Figure 32 one can launch nearly 90% of pump power into the fibre amplifier

Assuming 35% efficiency the saturated output power of the Example is in the region of 2.5 W. In many applications however required output power is 1 W which can be achieved with only 2.9 to 3 W of pump power, i.e. by using only two pump diodes. Thus by down-rating all four pump diodes to 800 mW one can achieve the required level of the output power. In the case of failure of one of the pump diodes, pump power from the rest is

increased to the level required to obtain a pre-determined level of the output power. Thus this system has protection against pump diode failure.

## EXAMPLE II

This Example is a mode-locked cladding pumped fibre laser with repetition rate frequency in the region of 50-200 MHz. The laser is based on the two fibre arrangement shown in Figure 40. The amplifying optical fibre has an OD of 80  $\mu\text{m}$ , core diameter of 15  $\mu\text{m}$  and signal NA of 0.07. The core is single-moded at the signal wavelength and made of Yb<sup>3+</sup>-activated aluminosilicate glass. The pump absorption cross section at 980 nm is  $20 \times 10^{-25} \text{ cm}^2$ , which implies an Yb<sup>3+</sup> concentration of 1000 particles per million (ppm). A 1 m long fibre absorbs approximately 90 % of launched pump power. The pump power is provided by 2 laser diodes with rated output power of 2 W.

With an appropriate mode-locking technique (either passive or active) the laser is capable of generating 1 ps pulses at repetition rate of 100 MHz and average power of 1 W and peak power in excess of 10 kW. Mirrors 401 form an optical resonator for the signal.

An advantage of using this configuration is that the signal and pump are spatially separated and thus high pulse peak power will not result in damage of pump diodes.



## EXAMPLE III

This Example is a multi-fibre arrangement including two or more pump diodes pumping simultaneously several amplifying optical fibres as shown in Figures 33 to 36. The amplifying optical fibres have an outer diameter (OD) of 100  $\mu\text{m}$  and a core diameter of 10  $\mu\text{m}$ . The core is single-mode at the signal wavelength and made of  $\text{Er}^{3+}/\text{Yb}^{3+}$ -activated aluminosilicate glass. The pump absorption cross section at 980 nm is  $20 \cdot 10^{-25} \text{ cm}^2$ , which implies an  $\text{Yb}^{3+}$  concentration of 9000 particles per million (ppm). A 5 m long fibre absorbs approximately 90 % of launched pump power. The pump power is provided by 4 laser diodes with rated output power of 2 W. Using the simple launching scheme shown in Figure 6 one can launch nearly 90% of pump power into the fibre amplifier. Assuming 35% efficiency the saturated output power of the Example is in the region of 1 W from each channel. It should be understood that total amount of output power available from all channels remains approximately the same so increasing the number of channels will result in decreasing of the output power from an individual channel. It should be also understood that it is preferred in a transmission system that optical power in any one channel should not exceed 10 to 15 mW to avoid non-linear effects. Thus if the number of doped fibres is equal to the number of channels, then the output power from the individual channels will be below 20 mW. The

present invention also makes it possible to increase the number of amplifying optical fibres to 16 or even 32 with the output power available from each channel in the region 50 –100 mW. To better appreciate the advantages of the coiled amplifying devices of Figures 41 to 47, some detailed examples of how pump light can be injected into the coil and converted to signal light are presented, and compared to the results obtainable with a prior-art, double-clad fibre laser.

#### EXAMPLE IV

This Example is a laser structure formed by coiling a fibre with a longitudinal pump absorption of 50 dB/m at 975 nm. The fibre has an outside diameter (“OD”) of 50  $\mu\text{m}$  and a core diameter of 10  $\mu\text{m}$ . The core is single-moded at the signal wavelength and made of  $\text{Yb}^{3+}$ -activated aluminosilicate glass. The pump absorption cross-section is  $20 \times 10^{-25} \text{ m}^2$ , which implies an  $\text{Yb}^{3+}$ -concentration of  $1.44 \times 10^{26} \text{ ions/m}^3$  or about 1.6% by weight. A 10 m long fibre is coiled to a torus of 10 cm diameter, i.e., with approximately 30 turns and with a cross-sectional area of approximately  $300 \times 300 \mu\text{m}^2$ . (Thus, the thickness of the torus is similar to the thickness of a typical double-clad fibre.) The output of three laser diodes, each at 2 W and with a 100  $\mu\text{m}$  wide stripe are injected into the torus with an overall efficiency of 75% via pump couplers made with 125  $\mu\text{m}$  diameter fibres and equally spaced along the torus. We estimate that the numerical aperture of

the pump beam injected into the torus is 0.2. The couplers are thus spaced by 10 cm. In order to absorb the pump, the beam should propagate approximately 20 cm (10 dB absorption) around the loop, and pass by another pump coupler a single time. We have estimated the excess loss for light propagating in the coil upon passing a pump coupler is negligible due to high numerical aperture of the coil and low numerical aperture of the pump optical fibre. Thus, the design allows essentially the entire pump power to be efficiently converted to signal.

#### EXAMPLE V

This Example is a laser structure formed by coiling a fibre with longitudinal pump absorption of 2 dB/m at 975 nm. The fibre has an OD of 250  $\mu\text{m}$  and a core diameter of 10  $\mu\text{m}$ . The core is single-moded at the signal wavelength and made of  $\text{Yb}^{3+}$ -activated aluminosilicate glass. The pump absorption cross-section is  $20 \times 10^{-25} \text{ m}^2$ , which implies an  $\text{Yb}^{3+}$ -concentration of  $1.44 \times 10^{26} \text{ ions/m}^3$  or about 1.6% by weight. A 200 m long fibre is coiled to a torus of 10 cm diameter, i.e., with approximately 600 turns and with a cross-sectional area of about  $6 \times 6 \text{ mm}^2$ . The output of 10 laser diode sources, each at 20 W and coupled to a fibre with 300  $\mu\text{m}$  diameter and with an NA of the beam of 0.2 are injected into the torus with an overall efficiency of 75% via pump couplers which are grouped into pairs and equally spaced along the torus. It is estimated that the numerical

aperture of a pump beam injected into the torus is 0.3. The couplers are thus spaced by 6 cm. In order to absorb the pump, the beam should propagate approximately 5 m (10 dB absorption) around the loop, and in this distance pass by a pump coupler 80 times. Since the pump couplers are a small perturbation on a thick torus, the excess loss for light propagating in the coil upon passing a pair of pump couplers will be small, in the region of 0.05 dB or 1%. Thus, with this design, approximately 70% of the pump power will be usefully absorbed by the  $\text{Yb}^{3+}$ , while the other 30% will be scattered by the pump couplers.

#### EXAMPLE VI

This Example is a laser structure formed by coiling a fibre with longitudinal pump absorption of 0.1 dB/m at 975 nm. The fibre has an OD of 1 mm and a core diameter of 10  $\mu\text{m}$ . The core is single-moded at the signal wavelength and made of  $\text{Yb}^{3+}$ -activated aluminosilicate glass. The pump absorption cross-section is  $20 \times 10^{-25} \text{ m}^2$ , which implies  $\text{Yb}^{3+}$ -concentration of  $1.15 \times 10^{26} \text{ ions/m}^3$  or about 1.3% by weight. A 100 m long fibre is coiled to a torus of 10 cm diameter, i.e., with approximately 300 turns and with a cross-sectional area of approximately  $17 \times 17 \text{ mm}^2$ . The output of 10 laser diode sources, each at 20 W and coupled to a fibre with 300  $\mu\text{m}$  diameter and with an NA of the beam of 0.2 are injected into the torus with an overall efficiency of 75% via pump couplers which are

grouped into pairs and equally spaced along the torus. We estimate that the numerical aperture of a pump beam injected into the torus is 0.3. The couplers are thus spaced by 6 cm. In order to absorb the pump, the beam should propagate approximately 100m (10dB absorption) around the loop, and in this distance pass by a pump coupler 1700 times. Because of the very small area of the pump coupler fibre compared to the torus, we estimate the excess loss for light propagating in the coil upon passing a pair of pump couplers to 0.1% (0.005 dB). Thus, approximately 55% of the pump power injected into the torus will be absorbed by the  $\text{Yb}^{3+}$ -ions, and 45% will be scattered by the pump couplers.

#### EXAMPLE VII

This Example is a fibre laser operating at 975 nm. It is well known that Yb ions in silica glass have a large emission cross-section at 975 nm which makes a Yb-doped fibre laser a candidate to replace conventional pigtailed laser diodes operating at this wavelength. Due to three level nature of the Yb-doped fibre laser at this wavelength the pump power intensity at the far end of the laser should be in the region of  $3 \cdot 10^4 \text{ W/cm}^2$  in order to ensure no signal absorption along the laser. This means that for a double clad fibre with a 200  $\mu\text{m}$  outer diameter, the pump-through power will be 10 W, which makes such a laser unpractical. Reducing the fibre OD to 20  $\mu\text{m}$  and transparency power to 100 mW could make this laser practical from the

required pump power point of view but fibre handling would be extremely difficult. Therefore all previous attempts to realise 975 nm fibre laser based on double clad fibre have had very limited success. As mentioned above, an advantage of the present configuration is that the pump intensity inside the laser can be made very high provided pump optical fibres are thin enough, which makes a high power 976 nm fibre laser feasible. One possible configuration is based on 4W pump diodes operating at 915 nm pigtailed to 200  $\mu\text{m}$  fibre. The fibre is silica rod with silicone rubber cladding. In reasonably short length the pump power NA can be kept as low as 0.1 which allows preservation of pump brightness by tapering output (uncoated) end of the fibre to 20  $\mu\text{m}$  so that pump intensity would be in the region of  $10^6$  W/cm<sup>2</sup>. 1m of Yb-doped fibre with pump absorption 10 dB/m at 915 nm is wrapped around a silica tube with 3 cm diameter. The fibre outer diameter is 120  $\mu\text{m}$  and doped core diameter is 10  $\mu\text{m}$ . The 975 nm laser threshold is estimated to be in the region of 1.2-1.5 W, slope efficiency in the region of 80%, and output power in the range of 1-1.5 W with one pump diode. Increasing number of pump diodes can scale up the output power.

There is given below the following advantages of coiled amplifying devices:

- i. NA = 1 suggests OD = 65  $\mu\text{m}$  for a 1 kW of pump (actually, NA > 1 for an air-clad fibre);
- ii. Fibre with OD = 1 mm is able to handle 4 kW of pump;

- iii. Structure similar to that shown in Fig. 8 can accept virtually unlimited amount of power (more than 10 kW);
- iv. Insofar as this is an all glass structure, preferably based on silica glass only, this type of fibre lasers does not suffer from thermal problems associated with pump absorption and thermally non-matching materials (glass and silicone rubber, for example);
- v. This type of fibre structure offer better pump absorption due to larger NA and non-azimuthally symmetrical cross section;
- vi. Pump power can be delivered to the system via dedicated pump optical fibres with OD = 200  $\mu\text{m}$ , NA = 0.2 which then can be tapered to 50  $\mu\text{m}$  (still no power loss). The use of modern adhesives can also be employed;
- vii. The number of pumps is virtually unlimited since by placing pump optical fibres at different azimuthal positions one can excite different modes - so there is no pump leakage at entrance points of adjacent pumps;
- viii. This system offers protection against pump diode failure;
- ix. Pump redundancy capability and flexibility in the range of output power make this type of fibre amplifier excellent candidate for leading amplifier for DWDM systems and satellite communications;

- x. Output power obtainable from this type of fibre lasers/amplifiers can be well beyond 100 W.

#### EXAMPLE VIII

This Example illustrates the advantages of a parallel optical amplifier 580 shown in Figure 58. The parallel optical amplifier 580 is a preferred embodiment of the parallel amplifier 500 that includes optical isolators 581, input fibres 582 and output fibres 583. The Example demonstrates drastically increased amplification capacity compared to the prior art in a compact, low-cost configuration.

The amplifier 580 has eight independent ports (or amplifying channels) that provide independent amplification, each port comprising the input fibre 582 connected to the isolator 583, connected to the amplifier 500, connected to another one of the isolators 582 that connects to the output fibre 583. Thus, the amplifier 580 can replace eight single-port amplifiers and bring down the amplifier count in a large system by nearly an order of magnitude.

Furthermore, as a result of the abundance of amplifier capacity, the amplifier 580 can be configured in different ways to fulfill different roles. This Example demonstrates cascading of ports to increase output power and bandwidth, as well as independent amplification of eight different wavelength channels.



The Example is based on an optical fibre arrangement that comprises eight Er/Yb co-doped amplifying optical fibres for signal amplification and two pump optical fibres arranged in such a way that pump power launched into one of the pump optical fibres crosses into all eight amplifying optical fibres via evanescent field coupling.

Each of the amplifier optical fibres 282 has a 100  $\mu\text{m}$  cladding and a 10  $\mu\text{m}$  core. The pump optical fibres 281 have a diameter of 125  $\mu\text{m}$ . Fibres coming out of the amplifier 500 were coated with UV curable secondary coating. Each end of the amplifying optical fibres 282 was then spliced to a different one of the optical isolators 581 so that the amplifier 580 can be considered as a set of eight independent fibre amplifiers.

The pump source 302 was provided by a module comprising six broad stripe 915 nm laser diodes coupled into a single 100  $\mu\text{m}$  core, 0.22 NA multimode optical fibre. The pump module had built-in laser diode driver and control electronics in a compact package. The pump module can provide up to 8W of pump power. The pump absorption of the amplifying optical fibre 282 at this wavelength was approximately 5 dB/m so that the length of each amplifier fibre was below 2 m.

The pump optical source 320 was connected to one end of a single single pump optical fibre 282. In this Example, the unabsorbed pump power was re-injected into the amplifier 500 by connecting the pump optical fibres 281 as shown.

The electrical current for the pump laser diodes was set at approximately 70% of its maximum value. This protected the amplifier 580 against diode failure: one or even two failed diodes can be compensated for by a larger pump current to restore the pre-set output power of the system.

Figure 59 depicts the spectral dependence of signal gain for two arbitrary amplifying channels. The gain curves for the other six channels were similar. The results demonstrate nearly identical performance of two independent amplifiers.

However, the saturation output power from each of the eight amplifiers varied from 15 – 18 dBm. The variation is caused by non-uniform pump power distribution between individual amplifying optical fibres. The uniformity can be improved by further developments of the system.

Figure 60 shows the noise figure. All eight amplifying channels offer a 1530 - 1570 nm gain bandwidth with noise figure below 5 dB. This is very close to data for conventional, core-pumped amplifiers. The total output power from the amplifier 580 is almost an order of magnitude higher.

The amplifier configuration allows two or more fibre amplifying channels to be cascaded (as described with reference to Figures 34 to 36) in order to increase the gain or saturated output power, while at the same time retaining the low noise figure. Figure 60 shows gain and noise figure for three cascaded amplifiers. The small signal gain exceeds 50 dB with a noise

figure still below 5 dB. The high gain and flexibility of the amplifier assembly allows, for example, for lossy elements like dispersion compensators or switches to be inserted between individual amplifiers, for added functionality without noise or power penalty.

The performance of the amplifying channels was also tested with an array of eight distributed feedback DFB fibre lasers with a 50 GHz signal spacing. The DFB fibre lasers were individually pumped and the output power was deliberately made unequal with more than 10 dB power variations. Figure 61 shows the output power in the individual wavelength channels 611, 612, 613, 614, 615, 616, 617, 618. The results demonstrate high contrast output spectra with significant power equalization.

Another way of using the amplifier 580 is for amplification of wavelength division multiplexed WDM signals, with the channels demultiplexed and then amplified in separate amplifying optical fibres. As seen in Figure 62, because of the use of a dedicated amplifying optical fibre for each WDM channel, the amplifier's inter-channel cross-talk is very low. The cross-talk was measurable only when three amplifiers were cascaded and is below -50 dB.

This Example has demonstrated a zero cross-talk parallel optical amplifier with small signal gain above 30 dB and noise figure below 5 dB. The system comprises eight, parallel, amplifying optical fibres pumped by a compact module with a built-in pump redundancy scheme. The amplifying

optical fibres have a length of 1.5 m, possess low cross-talk and low nonlinear signal distortion. The system can be reconfigured by cascading two or more amplifiers in order to increase gain or saturated power, retaining at the same time a very-low noise figure. This parallel amplifier is especially useful for application in wavelength-division-multiplexed telecommunication networks.

It is to be appreciated that the embodiments of the invention described above with reference to the accompanying drawings have been given by way of example only and that modifications and additional components may be provided to enhance the performance of the apparatus.

The present invention extends to the above mentioned features taken singularly or in any combination.

**Claims**

1. An optical fibre arrangement (70) comprising at least two optical fibre sections (71, 72), the optical fibre sections each having an outside longitudinally extending surface, and the outside longitudinally extending surfaces being in optical contact with each other.
2. An optical fibre arrangement (70) according to claim 1 in which the optical fibre sections (71, 72) are of constant cross-section.
3. An optical fibre arrangement (70) according to claim 1 or claim 2 in which the optical fibre sections (71, 72) are from the same optical fibre (81).
4. An optical fibre arrangement (70) according to claim 1 or claim 2 in which the optical fibre sections (71, 72) are from different optical fibres (91), (92).
5. An optical fibre arrangement (70) according to any one of the preceding claims in which the optical fibre sections (71, 72) are fused together.
6. An optical fibre arrangement (70) according to any one of the preceding claims in which the optical fibre sections (71, 72) are twisted about each other.
7. An optical fibre arrangement (70) according to any one of the preceding claims in which the optical fibre sections (71, 72) are

surrounded by a coating material along the length of the optical fibre arrangement.

8. An optical fibre arrangement (70) according to claim 7 in which the coating material is a polymer with a refractive index less than the refractive index of a cladding material of at least one of the optical fibre sections.
9. An optical fibre arrangement (70) according to claim 8 in which the coating material is silicone rubber.
10. An optical fibre arrangement (70) according to claim 6, claim 7 or claim 8 in which at least one of the optical fibre sections (71, 72) is individually separable by pulling from the remaining optical fibre section or sections.
11. An optical fibre arrangement (70) according to claim 10 in which the optical fibre arrangement (70) extends for a substantial length, and is in the form of an optical fibre cable.
12. An optical fibre arrangement (70) according to claim 6 in which the coating material is silica glass
13. An optical fibre arrangement (70) according to any one of the preceding claims in which at least one of the optical fibre sections (70), (71) is formed from a glass selected from the group comprising silica, doped silica, silicate, phosphate, and soft glass.

14. An optical fibre arrangement (70) according to any one of the preceding claims in which at least one of the optical fibre sections (70), (71) is an amplifying optical fibre.
15. An optical fibre arrangement (70) according to claim 14 in which the amplifying optical fibre comprises at least one rare earth dopant selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium Dysprosium or is doped with a transition metal or semiconductor.
16. An optical fibre arrangement (70) according to claim 14 or claim 15 and including at least one pump optical fibre, the pump optical fibre being in optical contact with the amplifying optical fibre along at least a portion of its length.
17. An optical fibre arrangement (70) according to claim 16 in which the pump optical fibre has a substantially uniform refractive index across its cross-section.
18. An optical fibre arrangement (70) according to claim 16 or claim 17 in which the pump optical fibre has a first diameter, and in which the amplifying optical fibre has a second diameter which is greater than the first diameter.
19. An amplifying optical device comprising an optical fibre arrangement (70) according to claim 14 or claim 15 and a pump

source, the amplifying optical device being configured such that the pump source illuminates the amplifying optical fibre.

20. An amplifying optical device comprising an optical fibre arrangement (70) according to claim 16, claim 17 or claim 18 and a pump source, the amplifying optical device being configured such that pump energy from the pump source is coupled to the pump optical fibre.
21. An amplifying optical device comprising an optical fibre arrangement (70) according to claim 10 and a pump source, in which the optical fibre sections comprise at least one amplifying optical fibre and at least one pump optical fibre, the amplifying optical fibre and the pump optical fibre being surrounded by the coating material along a first length, and in which the pump optical fibre is individually separable from the amplifying optical fibre and is connected to the pump source.
22. An amplifying optical device according to claim 20 or claim 21 and comprising at least two pump sources, the amplifying optical device being configured such that the two pump sources are connected to each end of the pump optical fibre.
23. An amplifying optical device according to claim 20, claim 21 or claim 22 and comprising a plurality of pump optical fibres, in which each end of the pump optical fibres is connected to a pump source



supplying pump energy, and in which the optical fibre arrangement (70) is configured such that a portion of the pump energy guided by each of the pump optical fibres is coupled into the amplifying optical fibre.

24. An amplifying optical device according to claim 20, claim 21 or claim 22 and comprising a plurality of pump optical fibres and a plurality of amplifying optical fibres, in which each end of the pump optical fibres is connected to a pump source supplying pump energy, and in which the optical fibre arrangement (70) is configured such that a portion of the optical energy guided by each of the pump optical fibres is coupled into at least one of the amplifying optical fibres.
25. An amplifying optical device according to claim 24 in which the plurality of amplifying optical fibres is configured such that optical radiation is guided more than once along the optical fibre arrangement.
26. An amplifying optical device according to any one of claim 19 - 25 and further comprising at least one optical element coupled along the length of the amplifying optical fibre, the optical element being selected from the group comprising a polariser, an isolator, a circulator, a grating, an optical fibre Bragg grating, a long-period grating, an acousto-optic modulator, an acousto-optic tuneable filter,

an optical filter, a Kerr cell, a Pockels cell, a dispersive element, a non-linear dispersive element, an optical switch, a phase modulator, a Lithium Niobate modulator, and an optical crystal.

27. An amplifying optical device according to claim 26 in which the grating is selected from the group comprising a gain-flattened grating, a dispersion compensating grating, and a gain-flattened, dispersion compensating grating.
28. An amplifying optical device according to any one of claims 19 to 27 in which the optical fibre arrangement (70) is formed as a coil.
29. An amplifying optical device according to claim 28 in which the amplifying optical fibre comprises a core and a cladding, the optical fibre arrangement (70) being such that the claddings of adjacent fibres of at least a pair of the turns touch one another.
30. An amplifying optical device according to claim 29, and including at least one pump optical fibre disposed with respect to the coil of amplifying optical fibre so that the pump optical fibre touches the amplifying optical fibre along at least a respective portion of its length.
31. An amplifying optical device according to claim 30 in which the pump optical fibre is disposed in interstitial gaps between turns of the amplifying optical fibre.

32. An amplifying optical device according to claim 30 or claim 32 and comprising a plurality of amplifying optical fibres.
33. An amplifying optical device according to any one of claims 30 to 32 in which the pump optical fibre is formed of a material having a lower melting point than the material of the amplifying fibre.
34. An amplifying optical device according to any one of the preceding claims in which at least a portion of the amplifying fibre is formed of single-clad uncoated optical fibre
35. An amplifying optical device according to claim 29 and including a light transmitting former, the amplifying fibre being wound around the former.
36. An amplifying optical device according to claim 35 and including a pump arrangement for launching pump light into the former.
37. An amplifying optical device according to claim 36 in which the pump arrangement comprises at least one pump optical fibre connected to a pump source and wound around the former to couple pump light into the former.
38. An amplifying optical device according to any one of claims 35 to 37 in which the former is a silica glass tube.

39. An optical fibre laser comprising an amplifying optical device according to any one of claims 19 to 38 and an optical feedback arrangement for promoting light generation within the laser.
40. An optical amplifier comprising an optical amplifying device according to any one of claims 19 to 38 in which there are a plurality of amplifying optical fibres.
41. An amplifier comprising a pump source supplying pump energy and an optical fibre arrangement (70) according to claim 1, and in which the optical fibre sections include at least one amplifying fibre and at least one pump optical fibre having two ends, the amplifier being configured such that the pump energy is coupled into the pump optical fibre from the pump source.
42. An amplifier according to claim 41 comprising a plurality of the amplifying fibres, each having an input and an output, the amplifier being configured such that the pump energy is shared by the plurality of amplifying fibres.
43. An amplifier according to claim 42 and configured such that at least one amplifying fibre is connected to another amplifying fibre.
44. An amplifier according to claim 42 in which the pump source contains at least one semiconductor laser diode.
45. An amplifier according to claim 42 or claim 44 and comprising at least one input fibre and a first multiplexer connected to the input

fibre, the amplifier being configured such that at least one of the amplifying optical fibres is connected to the first multiplexer.

46. An amplifier according to claim 45 and including, a coupler and at least one output port connected to the coupler, the amplifier being configured such that at least one of the amplifying optical fibres is connected to the coupler.
47. An amplifying arrangement comprising a plurality of amplifiers according to claim 45 or claim 46 and further comprising a second multiplexer connected to each first multiplexer.
48. An amplifying arrangement according to claim 46 or claim 47 comprising a plurality of amplifiers according to claim 45 and an optical device, the amplifying arrangement being configured such that the optical device is connected to the amplifiers.
49. An amplifying arrangement according to claim 48 in which there is at least one pump optical fibre shared between two of the amplifiers.
50. An amplifying arrangement according to claim 48 or claim 49 in which the optical device is selected from the group comprising an optical router, an add-drop multiplexer, an add multiplexer, a drop multiplexer, an optical switch, a polariser, an isolator, a circulator, a grating, an optical fibre Bragg grating, a long-period grating, an acousto-optic modulator, an acousto-optic tuneable filter, an optical filter, a Kerr cell, a Pockels cell, a dispersive element, a non-linear

dispersive element, an optical switch, a phase modulator, a Lithium Niobate modulator, and an optical crystal.

51. An amplifying arrangement according to claim 50 in which the optical device is an optical router comprising an optical switch configured such that optical signals output from one of the amplifiers are routed to at least two more of the amplifiers.
52. An amplifier according to claim 45 in which the first multiplexer is a wavelength division multiplexer.
53. An amplifier according to claim 45 or claim 52 in which in use signals from individual wavelength channels input to the amplifier are connected to different ones of the amplifying optical fibres.
54. An amplifying arrangement according to claim 47 in which in use signals from groups of individual wavelength channels input to the amplifier are connected to different ones of the amplifying optical fibres.
55. An amplifying arrangement according to claim 47 in which in use signals from individual wavelength channels input to the amplifying arrangement are connected to different ones of the amplifying optical fibres.
56. An amplifying arrangement according to claim 55 in which in use adjacent wavelength channels input to the amplifying arrangement are connected to different ones of the amplifiers.

57. A method for manufacturing an optical fibre arrangement (70) according to claim 1, which method comprises the following steps:
- providing a plurality of optical fibre preforms;
  - mounting the plurality of optical fibre preforms in a fibre drawing tower;
  - drawing a plurality of optical fibre from the plurality of optical fibre preforms under a drawing tension and at a drawing speed; and
  - twisting a plurality of optical fibre during the drawing process;
  - the drawing tension and the drawing speed being selected such that the outside surface of at least two adjacent optical fibres are in optical contact along at least a respective portion of its length.
58. A method according to claim 57 and further comprising passing the plurality of optical fibres through a coating cup.
59. A method for manufacturing an optical fibre arrangement (70) according to claim 1, which method comprises the following steps:
- providing a plurality of optical fibres;
  - pulling the plurality of optical fibres under a drawing tension and at a drawing speed; and
  - twisting the plurality of optical fibre during the drawing process;

- the drawing tension and the drawing speed being selected such that the outside surface of at least two adjacent optical fibres are in optical contact along at least a respective portion of its length.
60. A method according to claim 59 and further comprising passing the plurality of optical fibres through a coating cup.
61. A method for reducing the granularity in optical telecommunications network, which method comprises providing at least one of the amplifying optical arrangements according to any one of claims 47 to claim 51 in at least one location within the network.
62. An optical telecommunications network comprising at least one amplifying optical arrangements according to any one of claims 47 to claim 51.



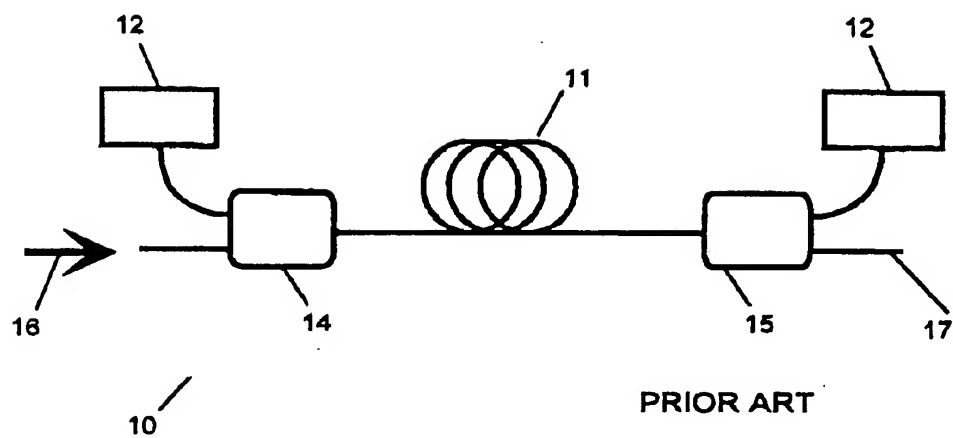


Figure 1

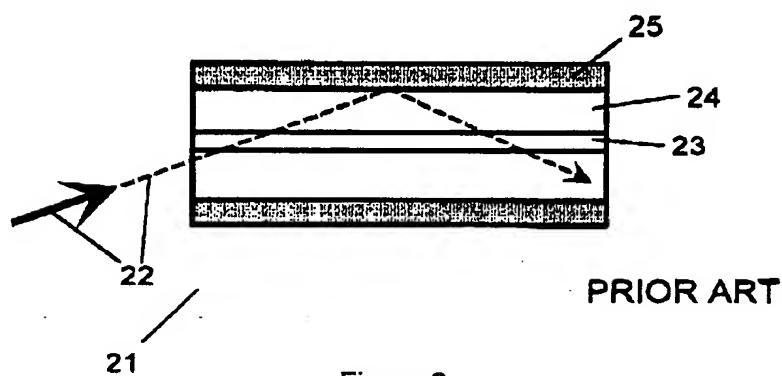


Figure 2

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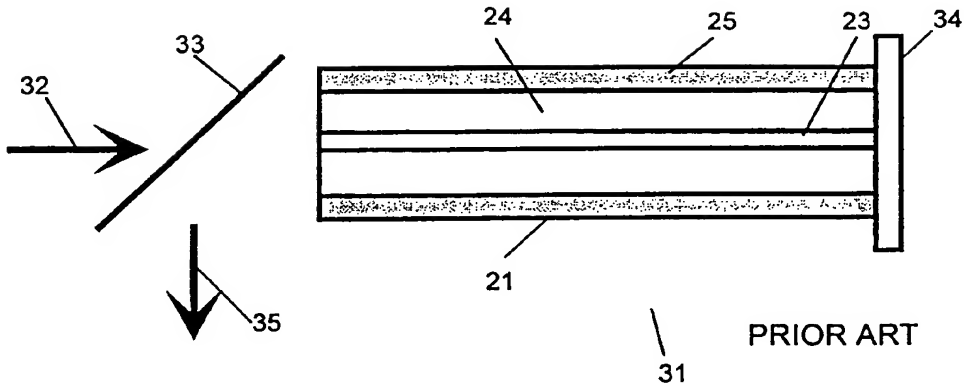


Figure 3

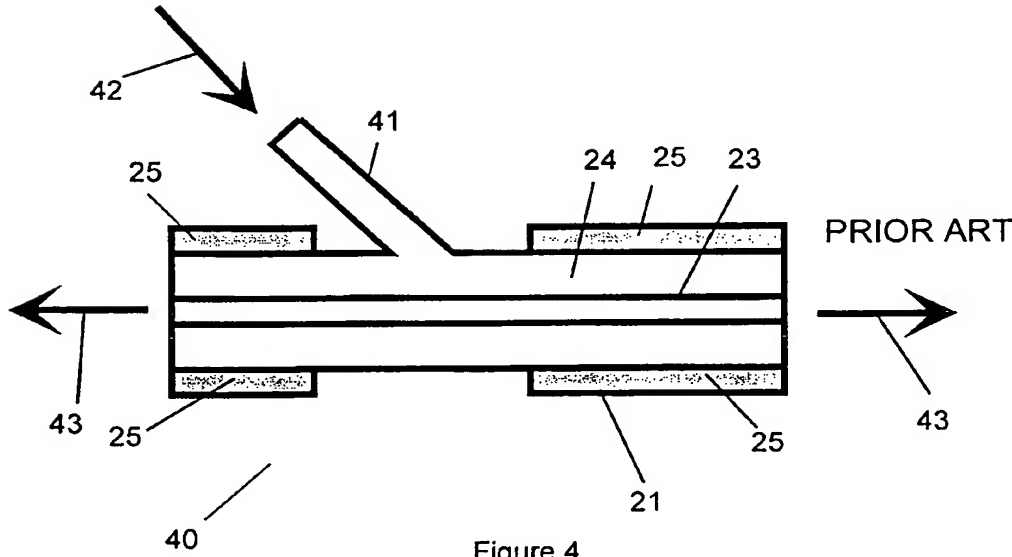


Figure 4

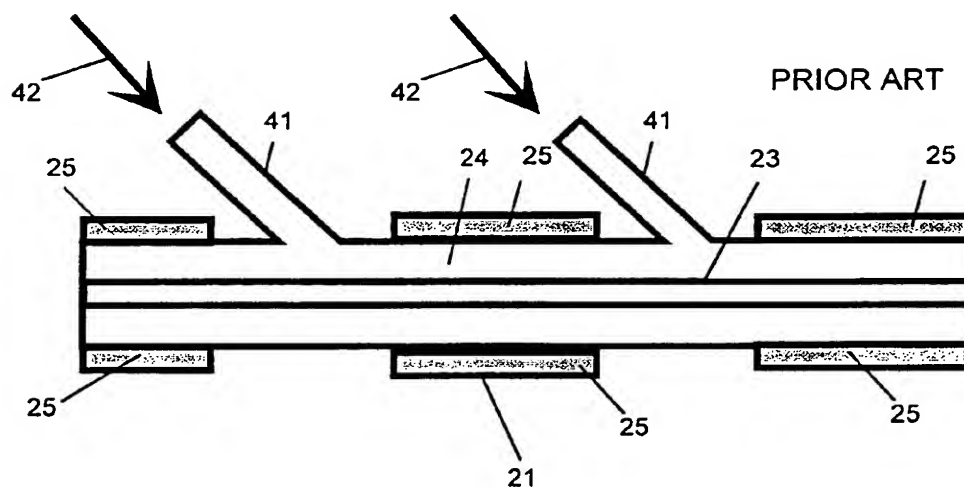


Figure 5

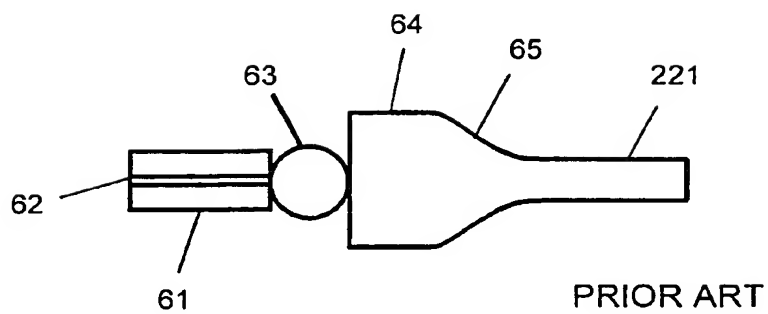


Figure 6

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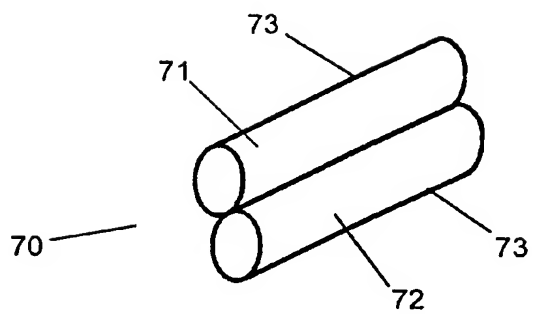


Figure 7

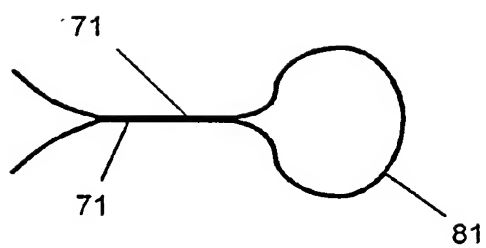


Figure 8

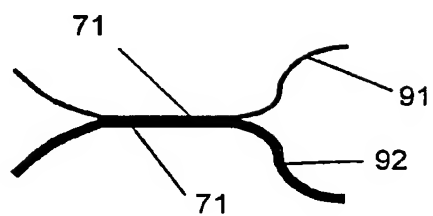


Figure 9

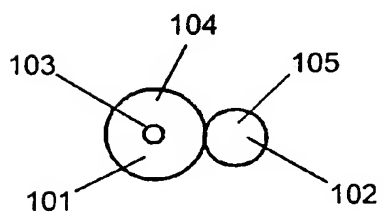


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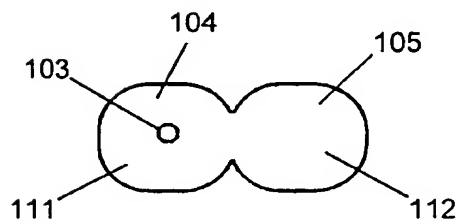


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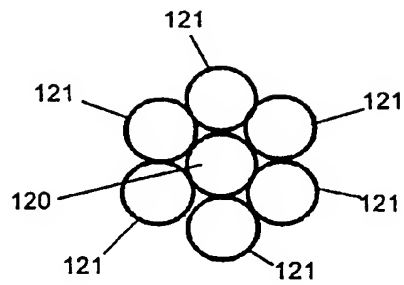


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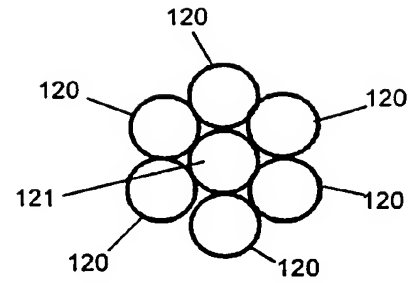


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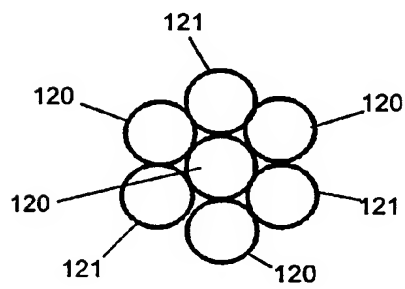


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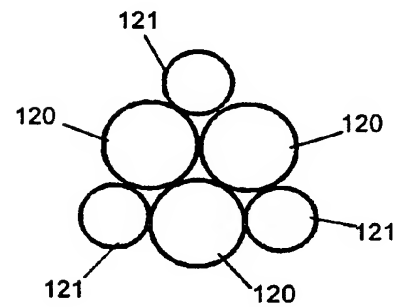


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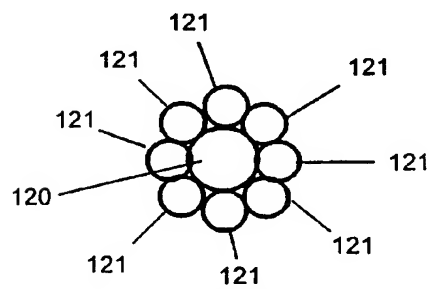


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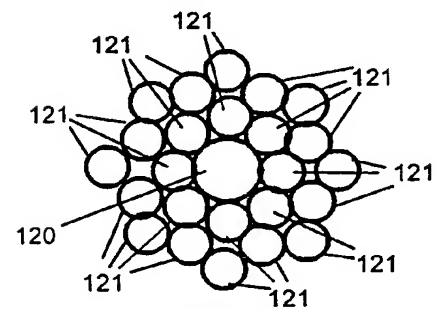


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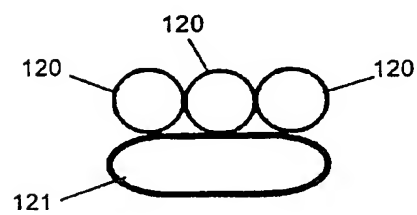


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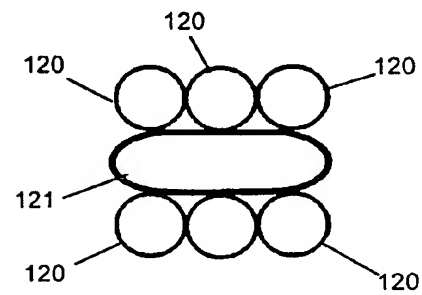


Figure 19

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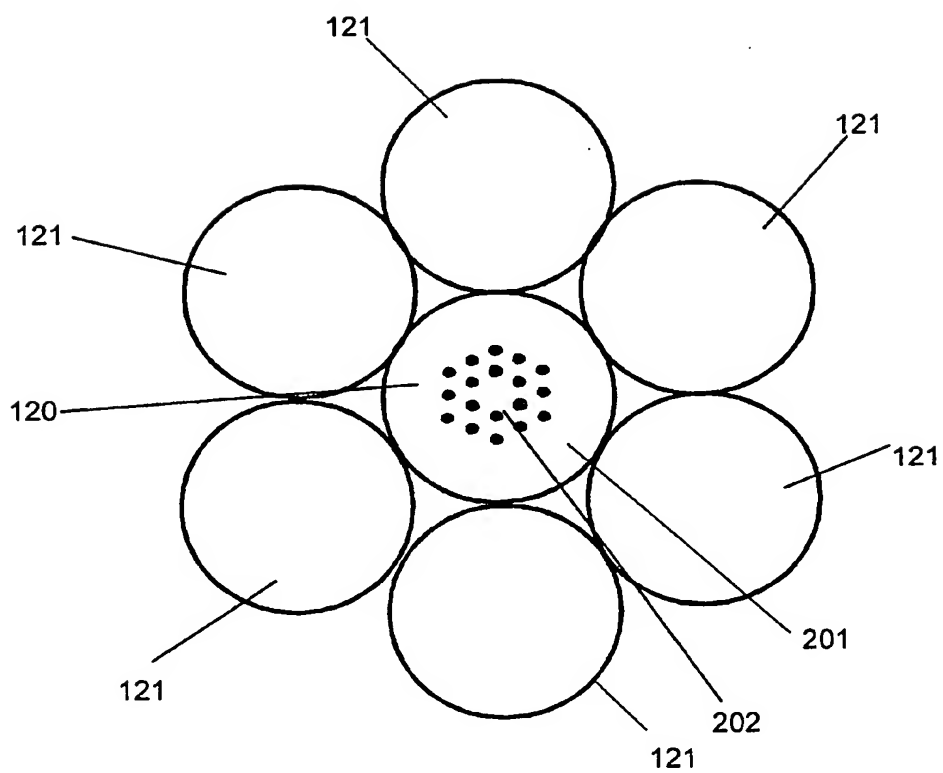


Figure 20

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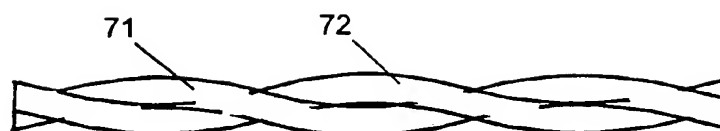


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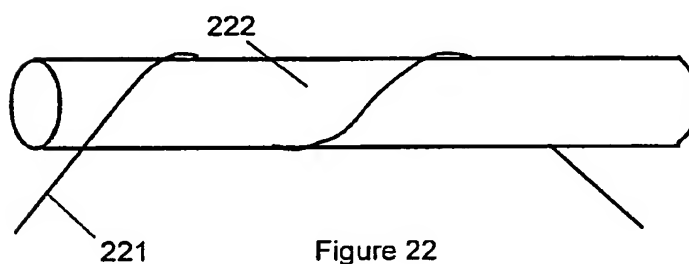


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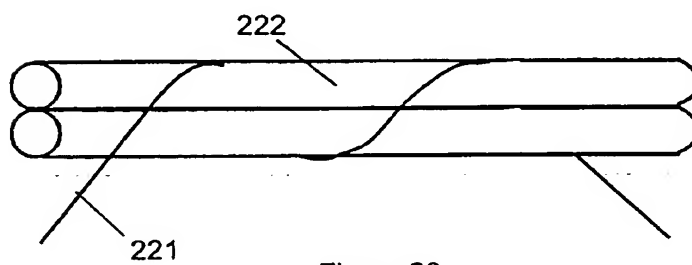


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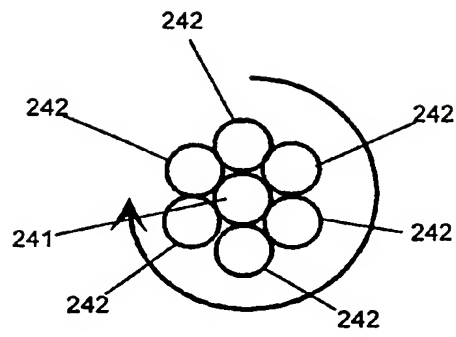


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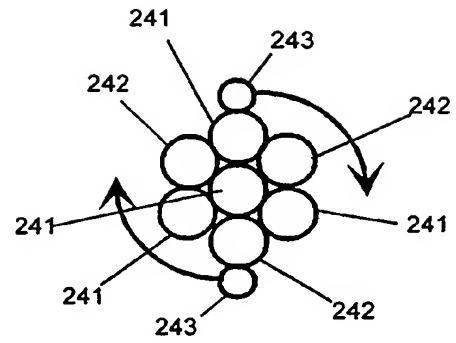


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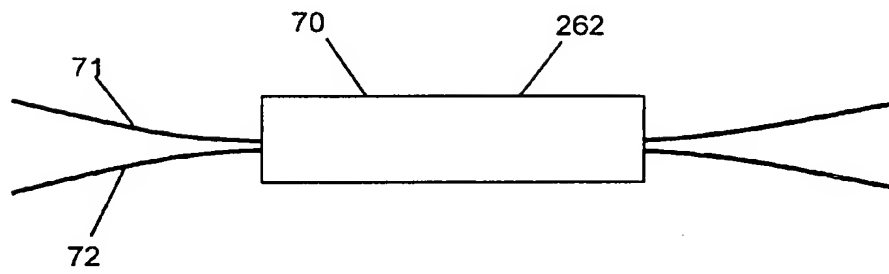


Figure 26



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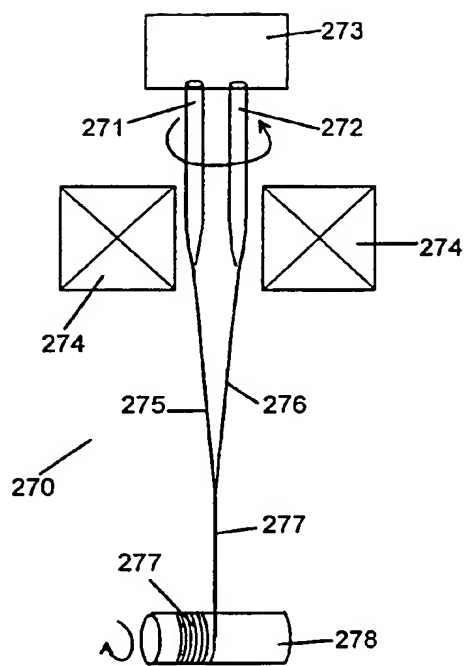


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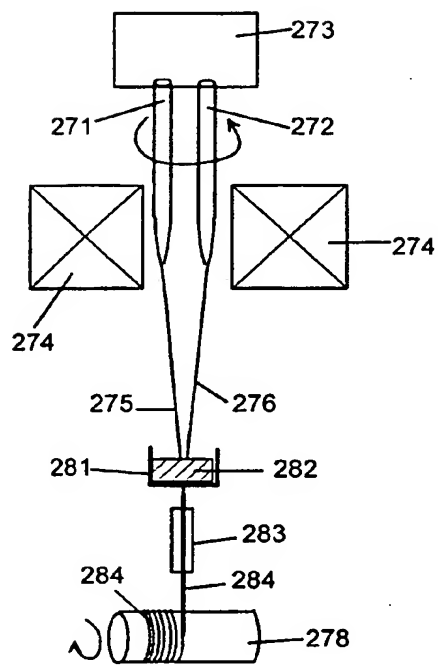


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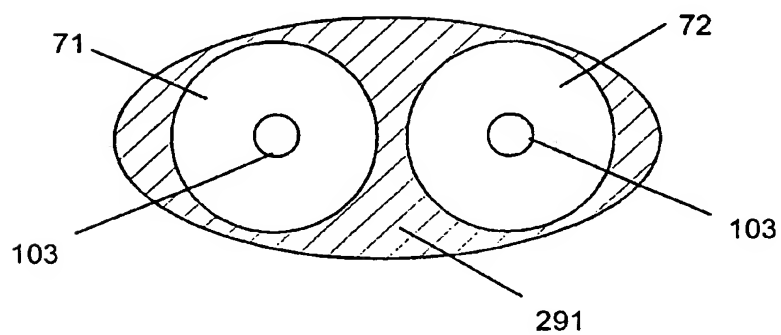


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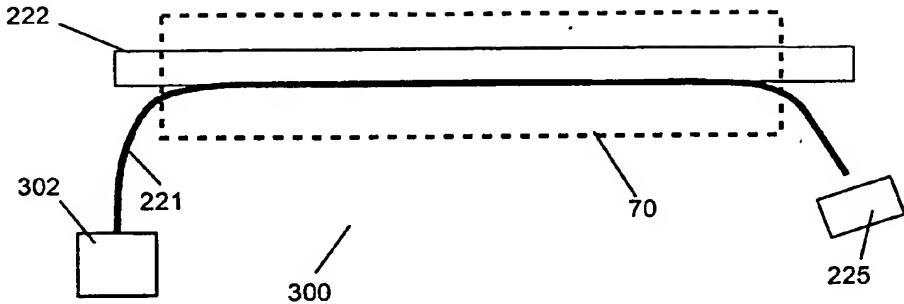


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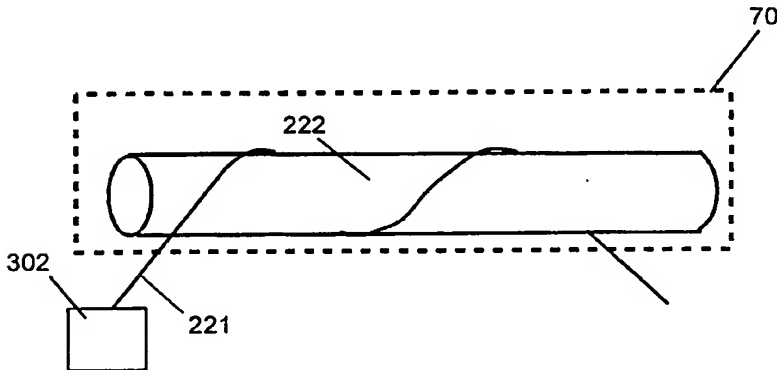


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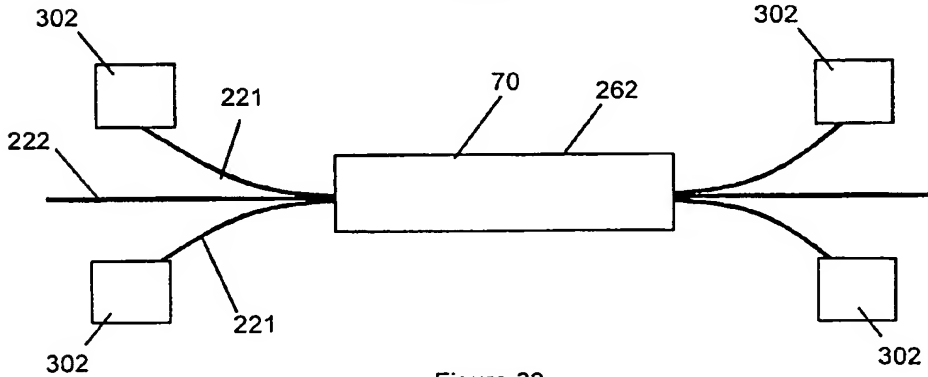


Figure 32

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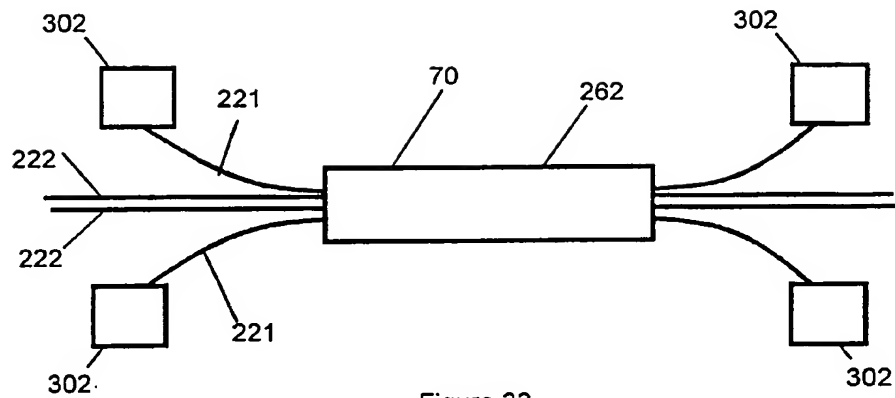


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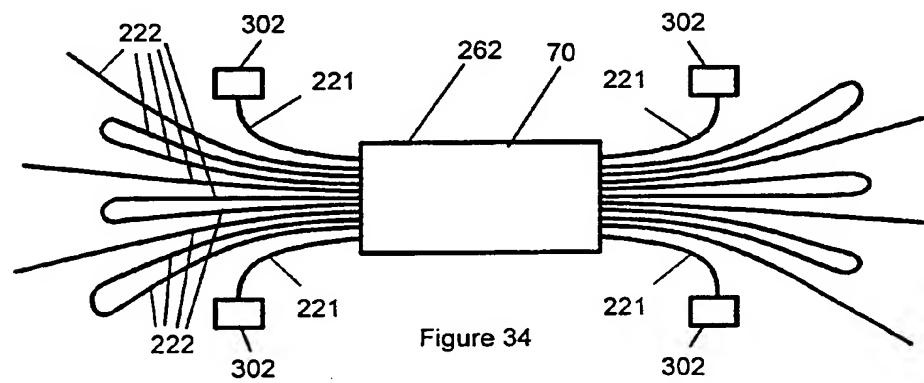


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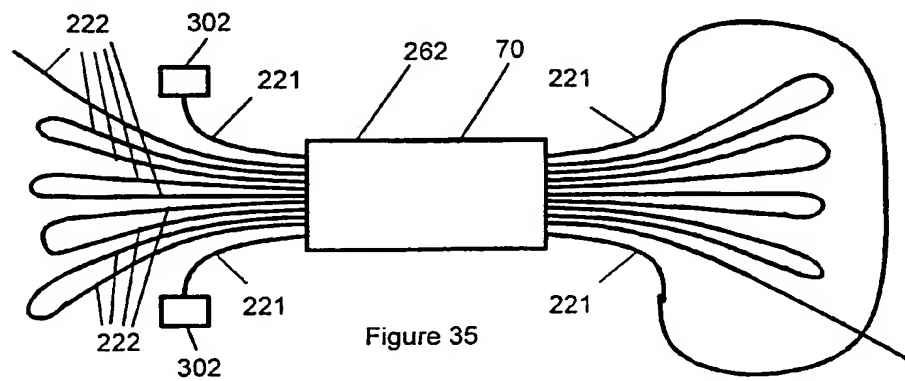


Figure 35

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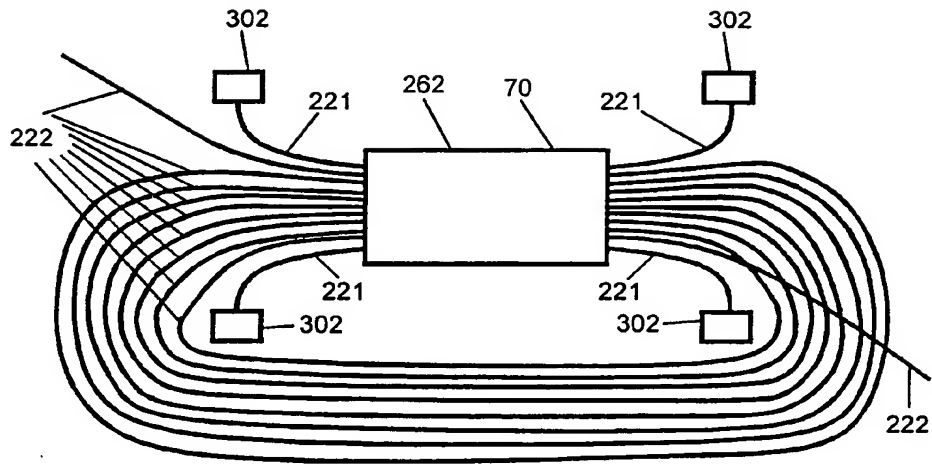


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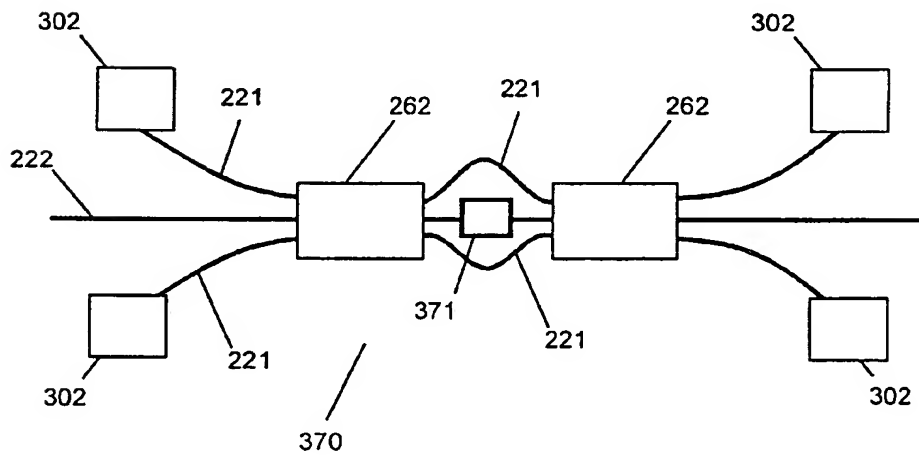
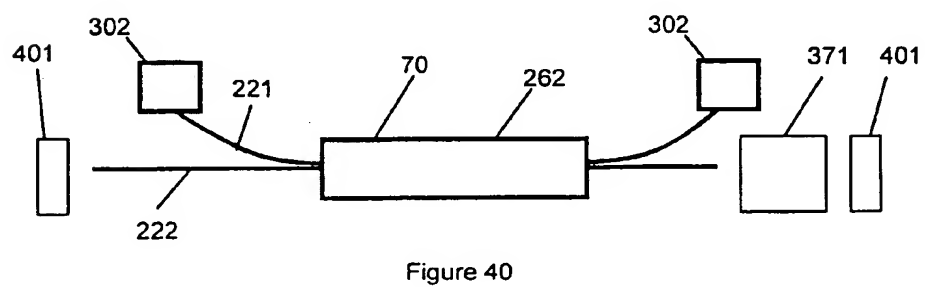
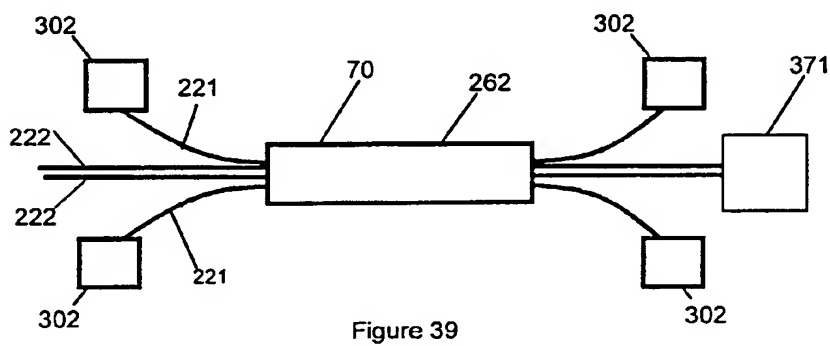
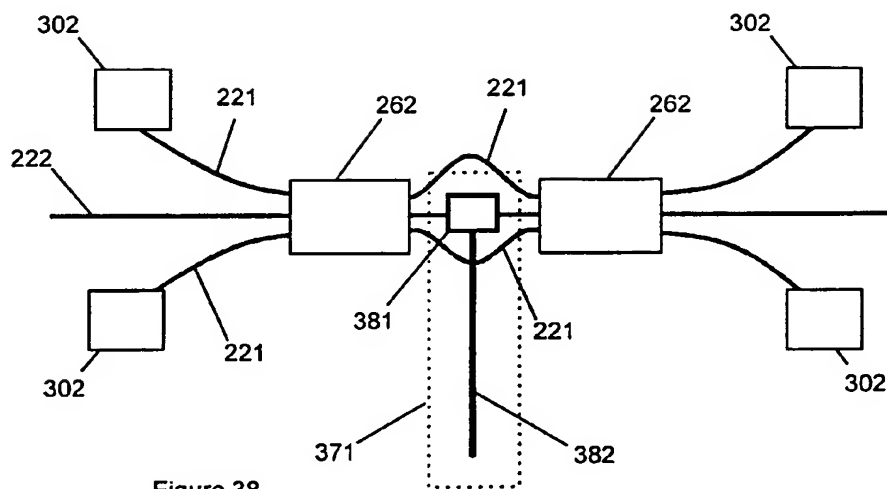


Figure 37

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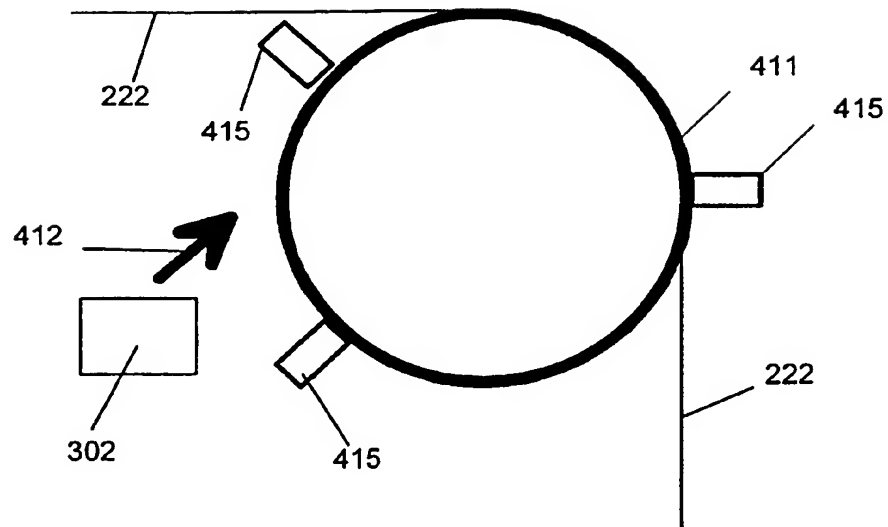


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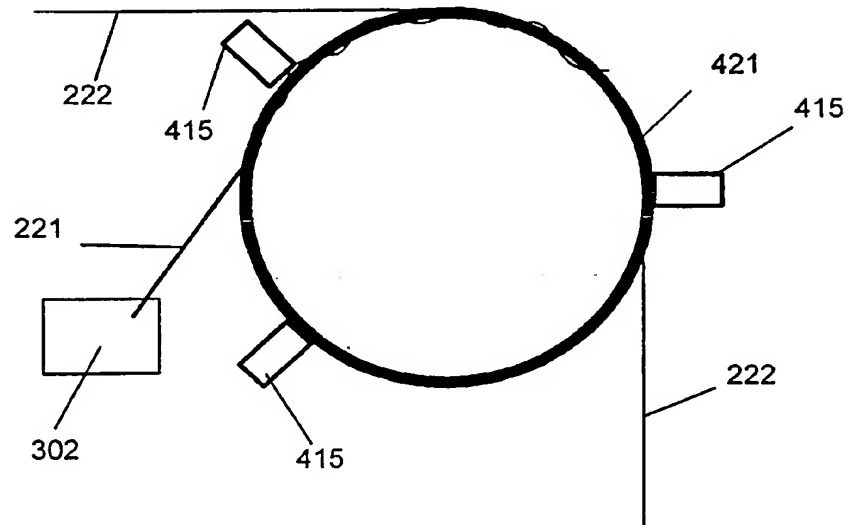


Figure 42

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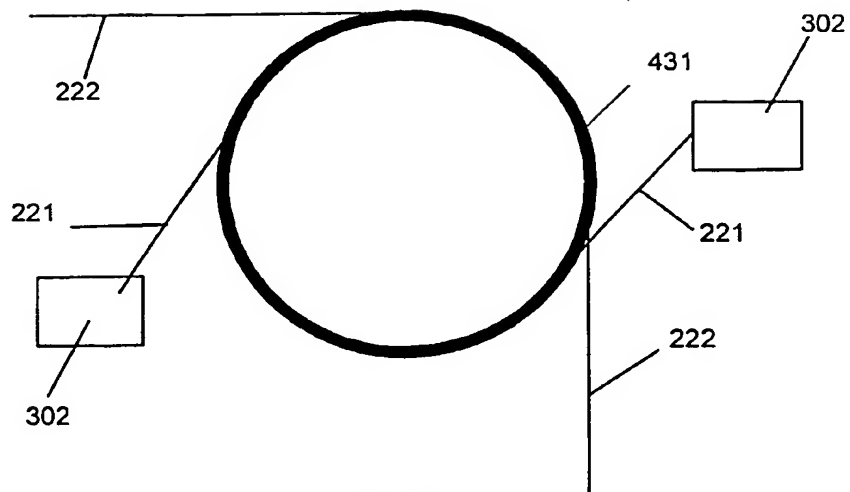


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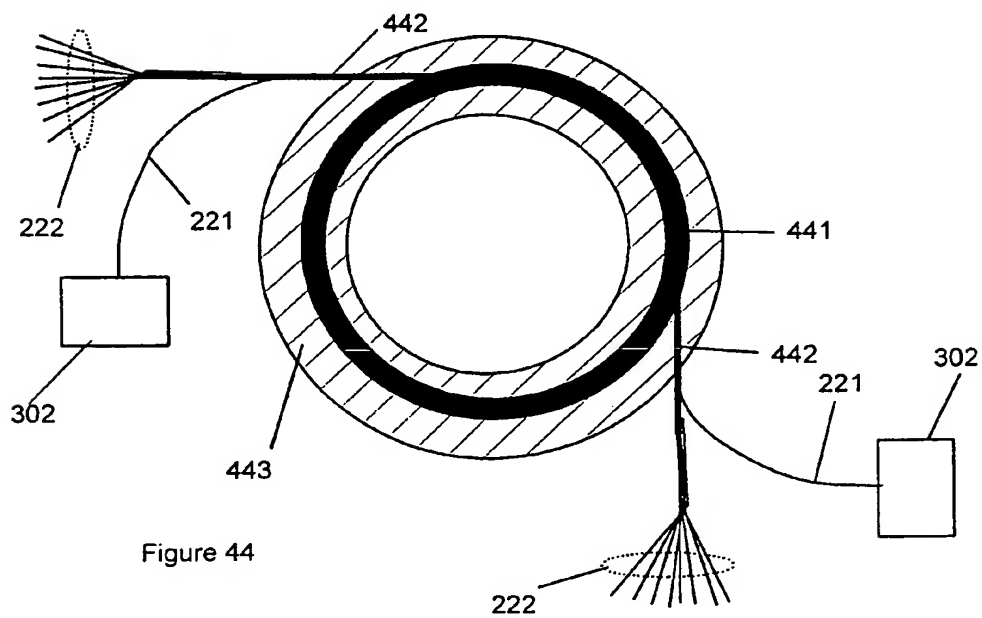


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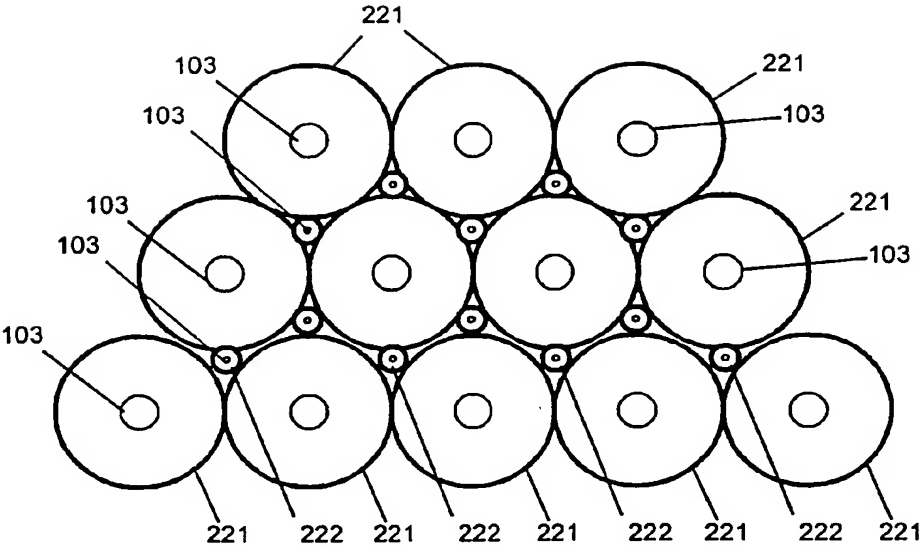


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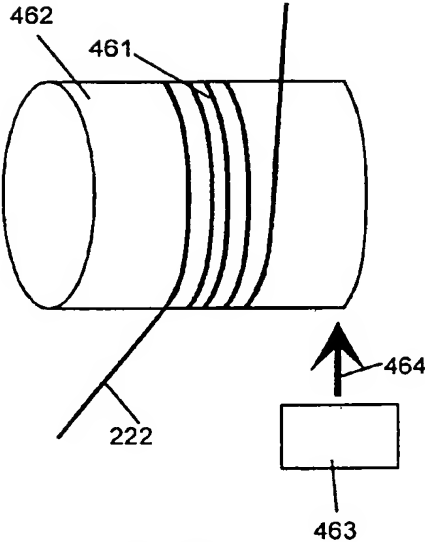


Figure 46

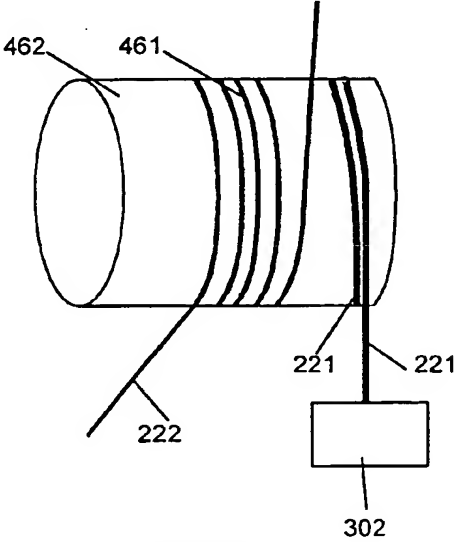


Figure 47



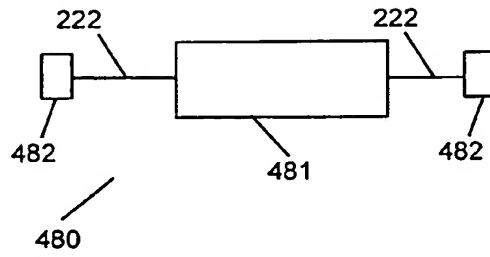


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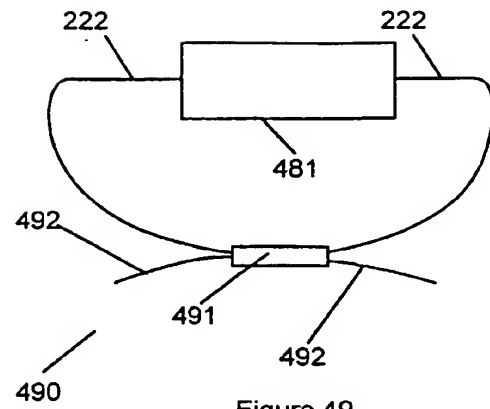


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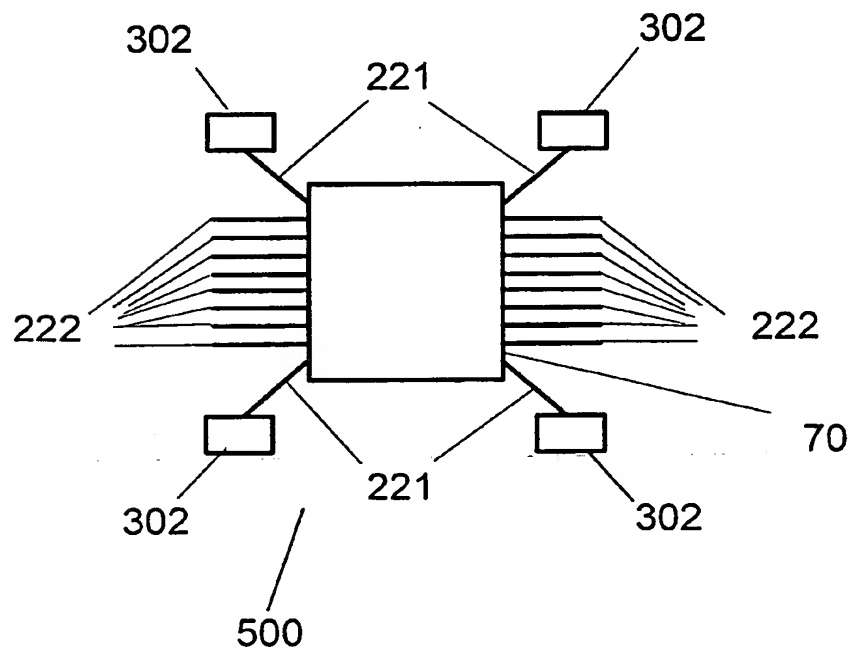


Figure 50

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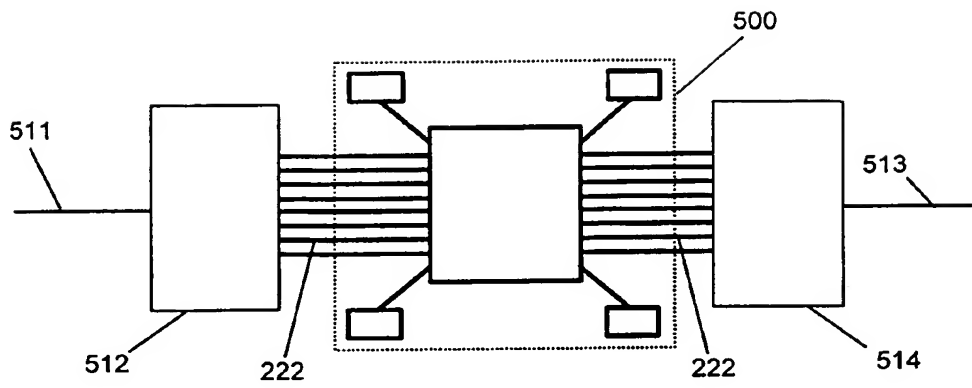


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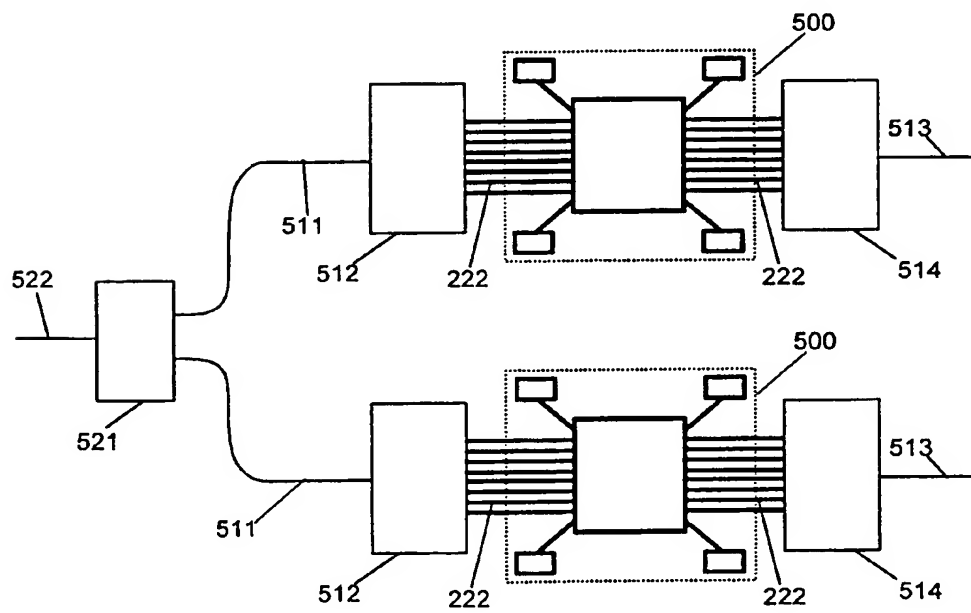


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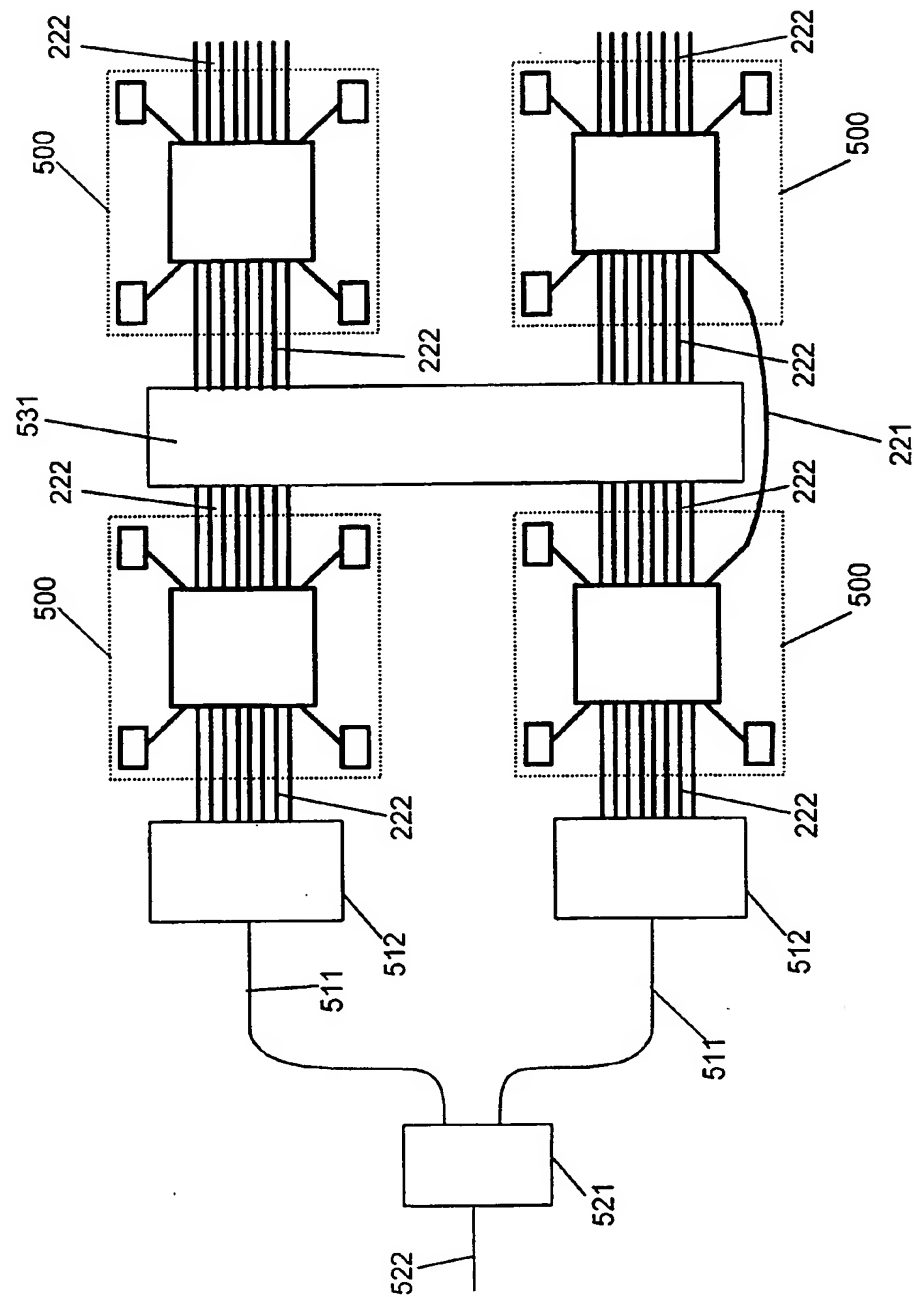


Figure 53

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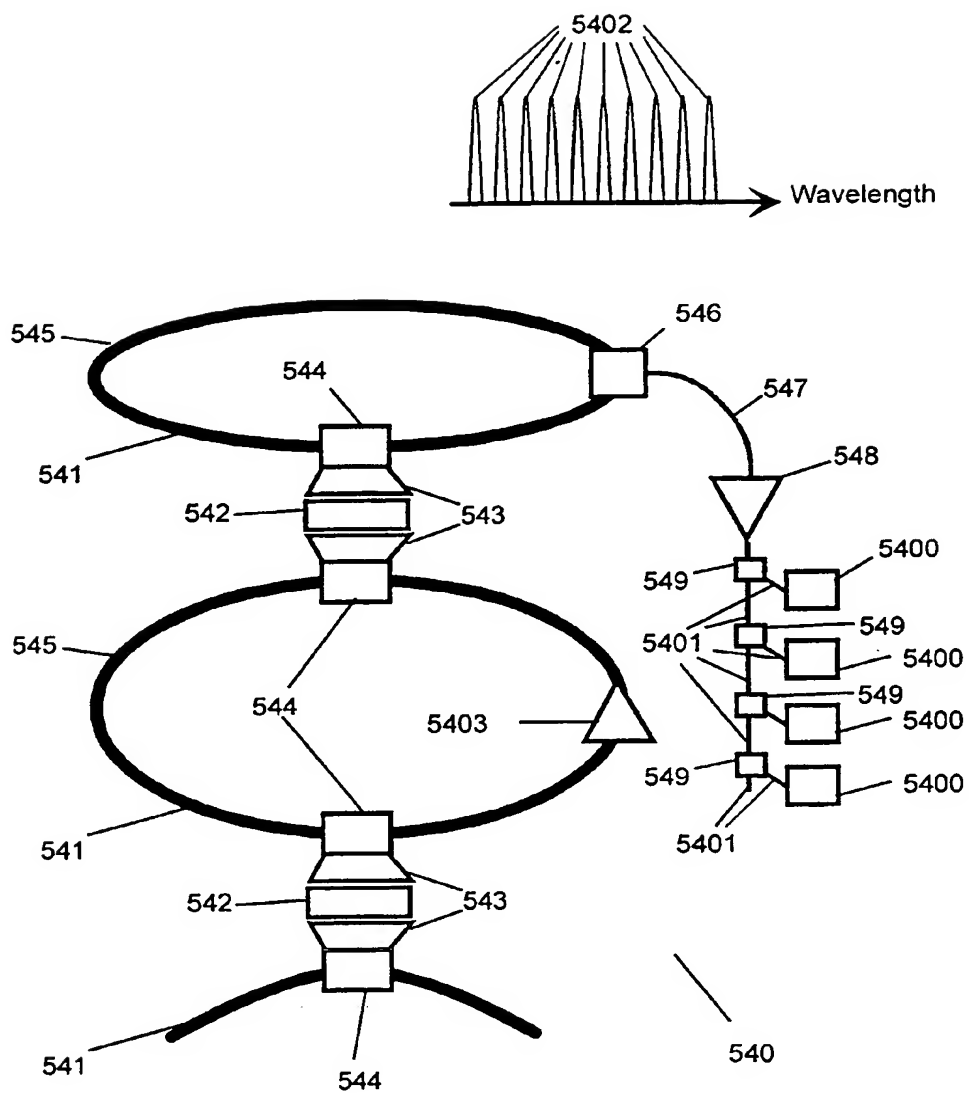


Figure 54

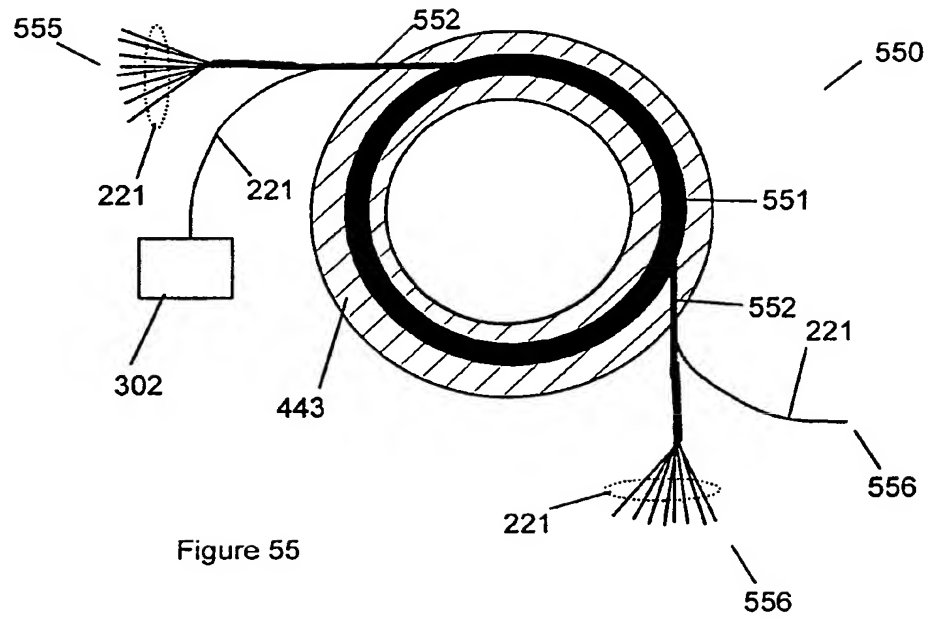


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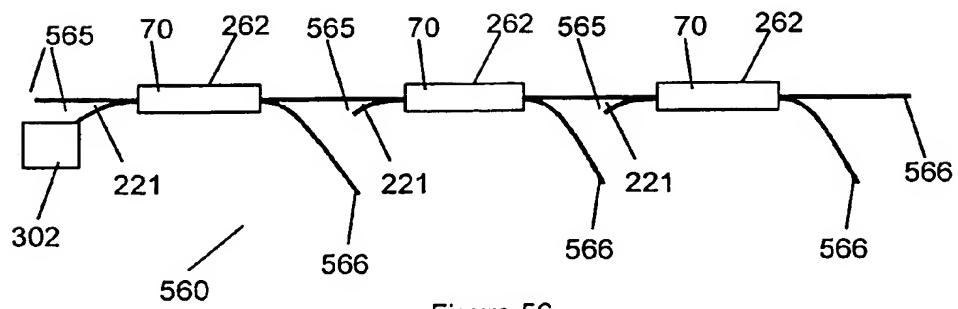


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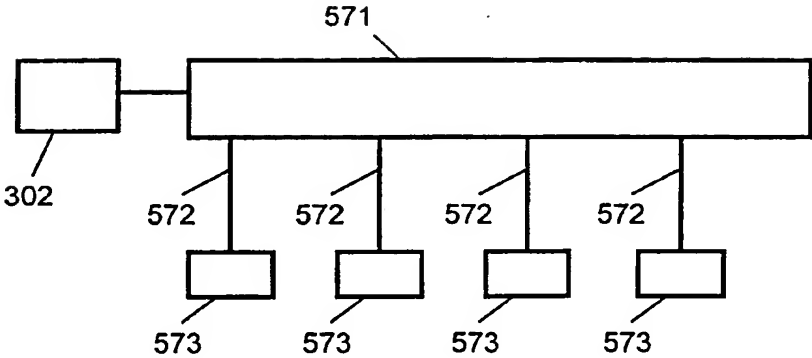


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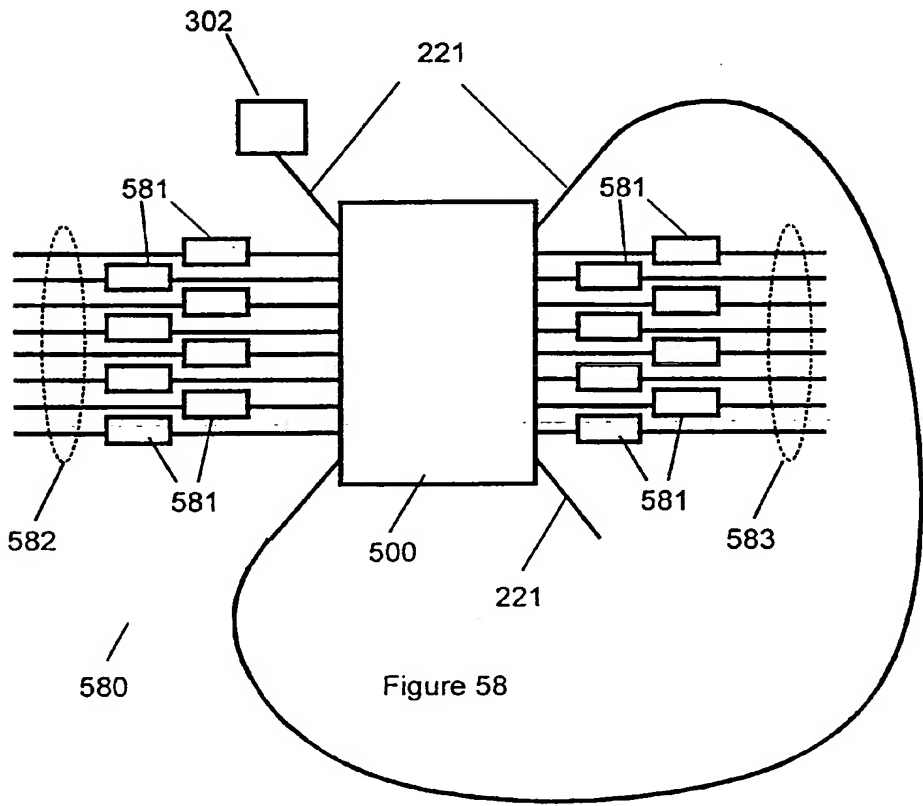


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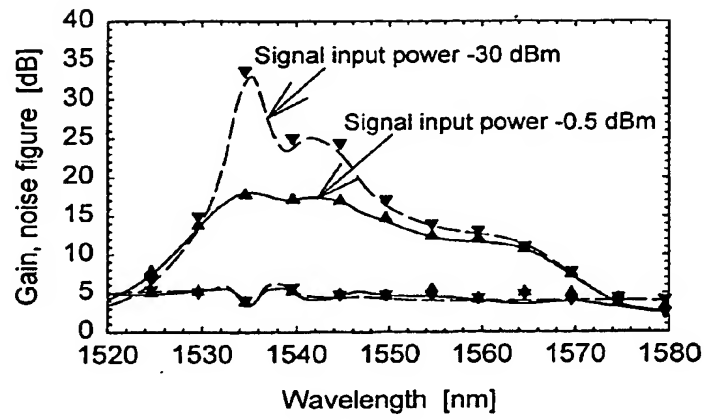


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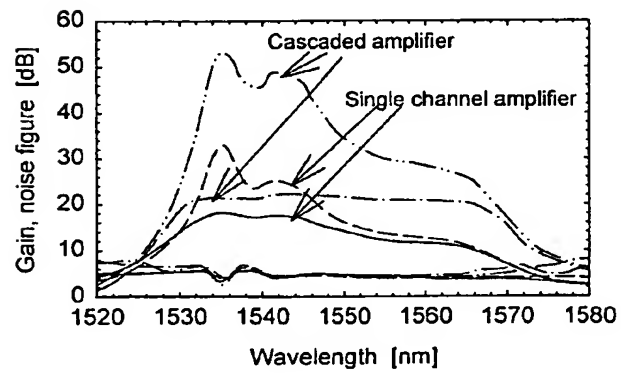


Figure 60

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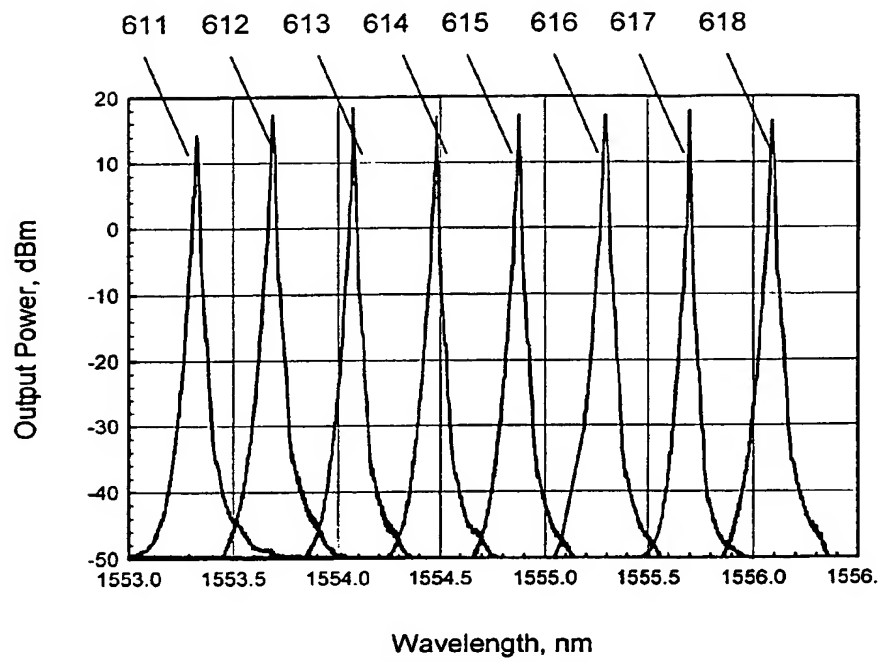


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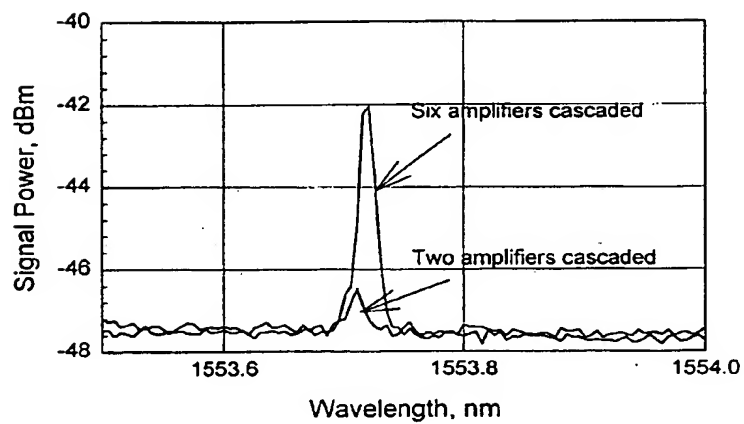


Figure 62



# INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 00/01664

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 7 H01S3/067 G02B6/28

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H01S G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, WPI Data

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4 815 079 A (HAKIMI FARHAD ET AL) 21 March 1989 (1989-03-21) cited in the application  column 4, line 63 -column 5, line 27; figure 3	1,2,4,5, 7,8,10, 13-23, 26-30, 34,39,41
X	WO 96 20519 A (ITALTEL SPA ;IRE POLUS CO (RU); SAMARTSEV IGOR (RU); GAPONTSEV VAL) 4 July 1996 (1996-07-04) abstract; figures 5,7,8  -/-	1,4-6, 10,11, 13-20

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

10 August 2000

Date of mailing of the international search report

17/08/2000

Name and mailing address of the ISA

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Galanti, M

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/GB 00/01664

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 050 173 A (HUGHES JOHN L) 17 September 1991 (1991-09-17)  figures 5,9	1-3,10, 11, 13-17, 19-21, 23-25, 28-32, 34,39-44
X	WO 97 39503 A (MASSACHUSETTS INST TECHNOLOGY) 23 October 1997 (1997-10-23)  abstract page 7, line 21 -page 8, line 2	1,2,4, 13-17, 19,20, 23,24, 41-44
X	US 4 553 238 A (DIGONNET MICHEL J F ET AL) 12 November 1985 (1985-11-12)  figures 1,2,9,10	1,2,4,7, 10, 14-17, 19-22, 39,41
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information on patent family members

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